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THE EFFECTS OF ACCOMMODATION, VERGENCE AND PUPIL SIZE ON SIZE ESTIMATION

FINAL REPORT

W.N.Charman and L-H Koh

Optometry and Vision Sciences, UMIST
PO Box 88, Manchester M60 1QD, UK

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Prof W. Neil Charman

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This report results from a contract tasking UMIST Ventures Office as follows: The contractor will determine the validity of various theoretical optical models in predicting changes in retinal image size and carry out a pilot study which monocular and binocular estimates of apparent size are made as a function rget distance and other parameters.

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CONTENTS

CHAPTER 1: INTRODUCTION

Several authors have suggested that inaccurate judgement of size and distance may be the cause of some flying accidents (e.g. Fuson, 1990; Roscoe, 1993). One hypothetical cause of such errors in size estimation is inappropriate accommodation, which is known to occur in a variety of conditions.

In its simplest form, the hypothesis suggests that the retinal image in the incorrectly-focused eye is larger than it would be in a correctly-focused eye, and that it is this difference in the size of the retinal image that leads to an incorrect judgement of distance. As was discussed in earlier reports (Interim and Final Reports Contract SPC-93-4052; Interim Report Contract SPC-95-4035), it seems highly unlikely the this hypothesis is correct. Nevertheless it remains possible that accommodation and the closely-related function of ocular convergence play a role in size judgement. There is a large literature going back many years which shows that when an object subtending a fixed angle at the eye is viewed, its apparent size diminishes as either the accommodation or convergence is increased (e.g. Wheatstone, 1852; Von Kries, 1924; Grant, 1942; Woodworth and Schlosberg, 1954; McCready, 1965; Komoda and Ono, 1974). These effects are known as accommodative and convergence micropsia.

The present study was designed to explore the effect of these and other relevant factors in more detail. Following an introductory survey of size and distance judgement, the question of whether accommodation-dependent changes in retinal image could account for the errors in size judgement reported in the literature is addressed. The results of a substantial study exploring the effects of viewing distance, pupil size, binocularity and field of view on size judgements are then reported. A pilot experiment to determine whether looming stimulates accommodation is then described. Finally, in view of the potential importance of binocular head-mounted and other virtual reality displays, two aspects of such displays are considered. First, since maladjustment of the optics of such displays may lead to unequal accommodative demands to the eyes, the question of whether, in binocular viewing, the eyes can accommodate unequally is studied experimentally; secondly the accommodation response to stereoscopic imagery is explored and compared to the result expected on the basis of the disparity of the images.

1.1 Some factors affecting the spatial perception of aircraft pilots

1.1.1 Perception of Objects in free space

Pilots perform a variety of critical tasks that require accurate distance and size estimation. For example, a helicopter pilot needs to manoeuvre the aircraft amongst trees and other obstacles, land in very low clearance areas, fly at low altitudes, and maintain a hover at a fixed altitude above a certain point. For safe operation, helicopter pilots must constantly verify that the aircraft has adequate clearance in all directions: the tail boom to the rear, the skids or wheels below, and the rotor blades above, to the sides, and in front. All must be clear of obstacles, sometimes by only a few feet, depending on the operational requirements. Thus the way the pilot perceives objects in free space during flying is important. The influence of ocular and non ocular factors on free space judgements of object size and distance will be explored in Chapter 3.

1.1.2 Looming

A pilot normally views his distant environment. As the plane flies towards the target, the angular subtense of the target at the pilots' eye will increase. The increase in angular size will be much more noticeable than the increase in the vergence of the target especially in an environment with less familiar visual cues (e.g. under a completely dark sky, or a completely strange environment like mountain and desert). This is due to the breakdown of size constancy perception. (Holway and Boring, 1941) Such "looming" of objects may affect the accommodation response of the eyes and, in turn affect the visual performance of the pilot, since inappropriate accommodation will cause blur in the retinal image and may also cause change in apparent size.

The effect of looming targets on the accommodative response is discussed in Chapter 4..

1.1.3 The eye's response to aniso-accommodative targets

The visual demands on a fighter pilot are particularly severe During an aircraft flight programme, continuous visual contact by the pilot with the outside world is required during landing, take-off, attack and terrain clearance. In each phase the

aircraft must be oriented with respect to the outside world. At speeds above 100 knots for landing and take-off and for higher speeds during attack and low-level flight, the pilot must have sufficient visual information to maintain a feel for the aircraft's position. If he takes his eyes away from the outside world to check instruments for speed, height, etc., the aircraft travels a considerable distance before he can re-focus his eyes to view what is by then a completely changed outside world. Then he must check all the visual cues once again. In an attack or landing situation, time is not on his side and mental activity directed towards re-establishing the visual cues obviously poses potential danger. Such potential danger can be overcome by using a head-up display (HUD) or a helmet mounted display (HMD) which allow the pilot to see the instrumental information without the need to shift or re-focus his eyes.

HUDs are virtual imaging displays commonly made in the form of head-up, narrow angle, combining glass presentations. HMDs are head mounted and include optoelectronics to project wide-angle sensor-generated or computer-animated imagery.

It is also common for pilots to wear night vision goggles at night to see the dark outside world.

Several potential problems may exist when the pilot uses such instruments. For example, flaws in the design or adjustment of an HMD may result in aniso-accommodative stimuli (Marran, 1995). How will the eyes respond to such targets? This is discussed in Chapter 5.

1.1.4 The eye's response to virtual reality (VR) images

It is common to use virtual reality systems to train pilots. These VR simulations cut down expenditure and prevent loses if "accidents" happen. It is common for participants in immersive virtual environments to suffer from a number of side effects, including nausea, malaise, disorientation and a variety of visual symptom. (Wilson, 1995). Could the dissociation of accommodation and convergence inherent in most VR systems cause asthesnopia when virtual images are viewed? Such effects will be discussed more fully in Chapter 6.

It will be helpful at this stage to review the literature covering these different areas.

1.2 Perception of objects in free space

How do we perceive the geometry of objects in free space? (i.e. when the environment is observed directly without any intervening optics.) In this report, we are particularly interested in the factors that affect the perception of an object's size (lateral dimension) and distance. Before these factors, are discussed further, three important laws/hypotheses for size-distance perception will be described. They are the size-distance invariance hypothesis (SDIH), the law of the visual angle, and the law of size constancy.

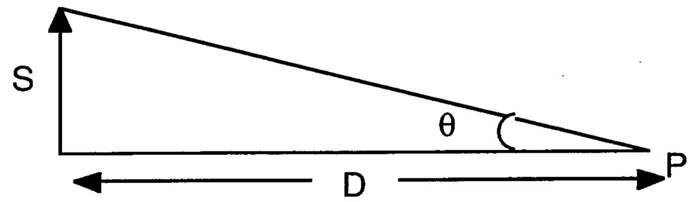
1.2.1 The "Size-Distance Invariance Hypothesis"

This hypothesis predicts that the ratio of perceived size to perceived distance is constant for a given visual angle, and that changes in the perceived size (lateral dimensions) of an object subtending a constant visual angle will be proportional to changes in the perceived distance of the object (Sedgwick, 1986). When applied to the projection of afterimages, this hypothesis is known as Emmert's Law (Weintraub and Gardner, 1970).

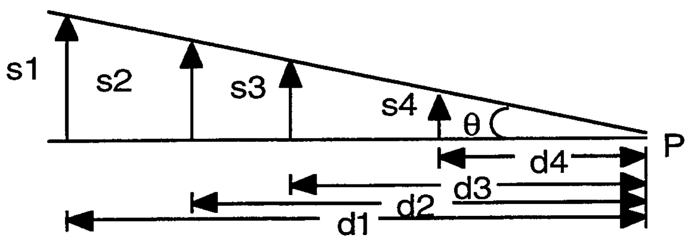
See figure 1.1. In order to maintain a given visual angle θ, as the distance of the distal stimulus increases, so must its physical size increase. In fact where **S** = stimulus size, **D** = stimulus distance, $\mathbf{S} = \mathbf{D} \times \tan\theta$.

Under the SDIH, the psychological (perceptual) relationships are described by the same function. The visual angle, i.e. the proximal stimulus, determines a unique ratio of perceived size (**s**) to perceived distance (**d**) such that $\mathbf{si/di} = \tan\theta$.

In other words, the perceived visual angle of an object is equal to its actual physical visual angle The law of the visual angle adopts this assumption.



(a) Physical relationship: $\tan \theta$ = **S/D**



(b) Perceptual relationships: **si/di** = $\tan \theta$

*Figure 1.1: Traditional formulation of the size-distance invariance hypothesis (SDIH). Physical relationships are shown in (a): An object of size **S** is at a distance **D** from an observer at point P. The stimulus at the eye is described by the visual angle θ, where tan θ = **S/D**. The psychological (perceptual) relationships described by the SDIH are shown in (b): The visual angle θ determines a unique ratio of perceived sizes (**si**) to perceived distances (**di**), **si/di** = tan θ. (Hershenson ,1989)*

1.2.2 The "Law of the Visual Angle"

The law of the visual angle states that accommodated objects which subtend equal visual angles are equal in apparent size (Holway and Boring, 1941). Refer to figure 1.2. If the angle θs, subtended by a standard stimulus, is equal to the angle θc, subtended by a comparison stimulus, then:

$\tan \theta c = \tan \theta s$ and

$Sc = (Dc/Ds)Ss$

where Sc = the linear size of the comparison object;

Ss = linear size of the standard object;

Dc= the distance from the eye to the comparison object;

Ds = the distance from the eye to the standard object.

Refer to figure 1.2. SDIH assumes that the size of the optical image on the retina is a peripheral determinant of visual size, and if all other determinants were constant, perceived size would vary directly with the visual angle. However, it has been known for some time that the visual angle does not provide a consistent measure of perceived size (Holway and Boring, 1941). An example of phenomena which violate SDIH is size constancy.

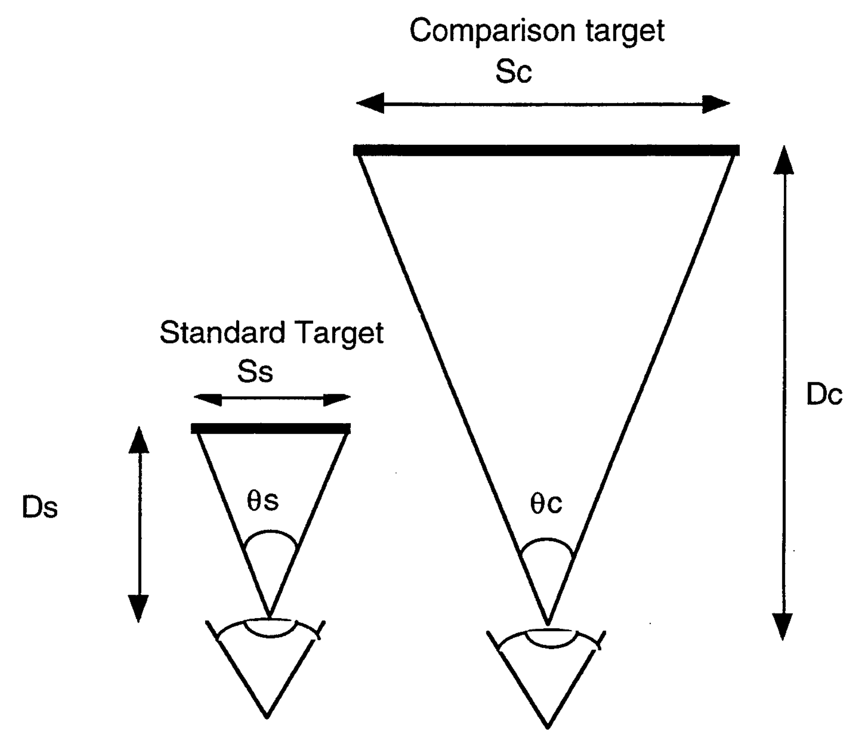


Figure 1.2: Law of the visual angle: Angle θs = Angle θc

1.2.3 Size Constancy

Size constancy is the ability of an observer to make cognitive adjustments for viewing distance so that, when an observed target approaches and its retinal image expands, its perceived size is taken as constant; the object is not perceived as actually becoming larger, expanding like an inflating balloon.

Leibowitz (1974) considered that size constancy was controlled by a number of mechanisms, which were classified into 3 categories:

i. Conceptualisation of size based on information provided through language without additional sensory stimulation.

ii. Perceptual learning including both language-based information gathering and non-linguistic learning.

iii. Oculomotor adjustments for accommodation and convergence.

As will be discussed later, the phenomena of convergence micropsia and accommodative micropsia do, in fact, involve size changes in the direction that would contribute to perceived constancy of size, but the effects are typically of such relatively small magnitude that there is no justification other than analogy for linking micropsia to the cognitive processes underlying size constancy (McCready, 1965). To further support this claim, Enright (1989a, b) in his experiment on the moon illusion managed to evoke about 30% reduction in apparent size with a 1 degree change in vergence, in a situation where true size constancy would have required a thousand-fold decrease.

As early as the 19th century, Helmholtz (cited by Koenigsberger, 1965) had mentioned that seeing was a learned response, and more recently McKee and Welch (1992) suggested that size constancy might be a learned response too. Welpe (1979) showed the cortical origin of the size constancy mechanism. Leibowitz and Heisel (1958), Hanely and Zerbolio (1965), Leibowitz and Judischr (1967) and Farquar and Leibowitz (1971) all consistently demonstrated that size constancy for distant objects increases as a function of chronological age, hence presumably with experience in the environment.

One hypothesis of size constancy is that phenomenal size is determined by the size of the retinal image of an object in relation to that of neighbouring object images, that is, a size ratio principle. Because the size of object "A" in relation to that of neighbouring object "B" (both at the same distances from the observer) remains constant for all distances of the pair of objects, the observer will experience size constancy. According to this hypothesis, a cue rich environment will have more neighbouring objects and thus facilitate size constancy.

Size constancy and other perceptual constancies enable us to see a stable world. Only in unusual circumstances can we detect the tremendous changes of retinal

image size in proximal stimulation as we walk about. Thus size constancy tends to break down under "reduced" conditions such as monocular vision, dim illumination, and restricted field of view (Holway and Boring, 1941), and in the presence of unfamiliar objects. Normally a person does not appear to double in size with each couple of steps.

The law of size constancy when represented in a formula, simply states: **Sc = Ss**, where **Sc** and **Ss** are the linear sizes (lateral dimensions) of the comparison object and standard object respectively. This formula means that the size of the comparison target is equal to the size of the standard irrespective of their distances from the eye. (Figure 1.3).

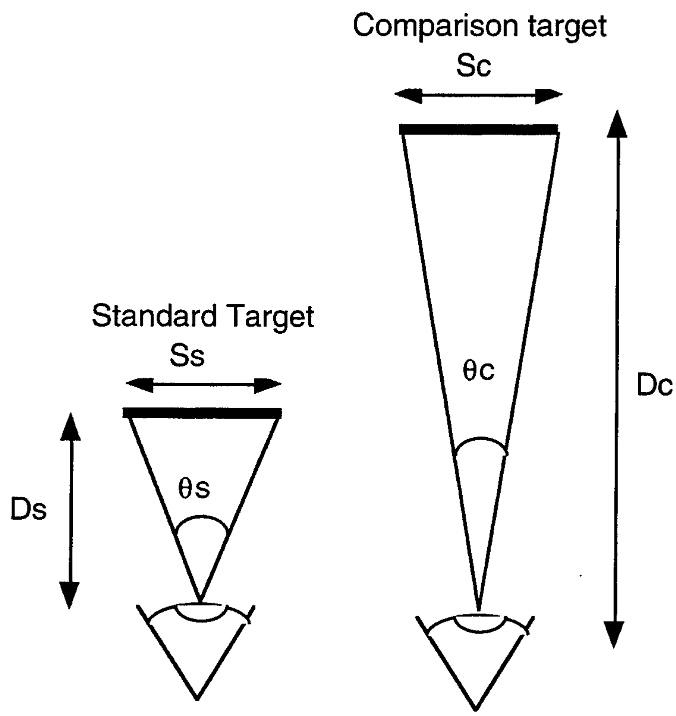


Figure 1.3: Size Constancy: Sc = Ss

1.2.4 Factors affecting size and distance judgements

Two major classes of factors, ocular and non-ocular, affect the way we perceive size and distance. The ocular factors will be described first:

1.2.4.1 Ocular factors

Variables that may affect perceived size include accommodation, the vergence of the eyes, dark adaptation, elevation of the head and eyes, binocularity versus monocularity, and retinal stretching during accommodation.

1.2.4.1.1 Accommodation

Accommodation is the mechanism by which the focus of the eye is shortened through the contraction of the ciliary muscle, increasing the convexity of the lens.

When an object subtending a fixed angle at the eye is observed, its apparent size diminishes as accommodation is increased. (e.g. Wheatstone, 1852; Von Kries, 1924; Grant, 1942; Woodworth and Schlosberg, 1954; McCready, 1965; Komoda and Ono, 1974; Roscoe, 1985; Meehan, 1995). This effect is known as accommodative micropsia. This phenomenon is discussed in chapter 2.

1.2.4.1.2 Vergence

Vergence is a disjunctive reciprocal motion of the eyes. It consists of convergence and divergence.

Convergence is a disjunctive movement of the eyes whereby the fixation axes, instead of remaining parallel, become inclined towards each other, so allowing a near object to be fixated and fusion maintained. Convergence can be induced by a stimulus to accommodate. This is known as accommodative convergence. Maddox (1893) stated that the amount of accommodative convergence was a function of the amount of accommodation required for accurate focus. Thus convergence is coupled with accommodation.

Divergence is a binocular abduction of the eyes from the mid-line.

How then can convergence and divergence affect size and distance judgement? As early as 1852, Wheatstone described the effect of vergence changes on the perceived size of observed objects. Convergence caused a shrinkage in size, divergence an enlargement.

This phenomenon has been named convergence micropsia: a change in perceived size which is due to convergence/divergence of the visual axes. Convergence micropsia has been quantified by Heinemann and Nachmias (1959), but no plausible physiological explanation for the perceptual anomaly has yet been proposed.

Convergence also affects distance judgement. Bourdy et al., (1991) suggested that people with overconvergence in darkness underestimate distances and people with underconvergence in darkness overestimate distances. Their study of bipartition in depth of a given interval for different observational distances confirms the existence of these two major categories of individuals. That is, overestimation or underestimation of distances seems to be correlated with the behaviour of binocular dark convergence specific to each individual.

Hollins and Bunn (1977) showed that convergence micropsia was more prominent with foveal viewing than with non-foveal viewing regardless of monocular or binocular observation. For their 2 subjects considered together, convergence micropsia was only 46% as great at 5°, and 19% as great at 10°, as it was with foveal viewing.

Enright (1989a) demonstrated that the magnitude of the perceived change in size of a target, due to vergence changes, depended on stimulus context. An empty visual surround reduced micropsia by more than half, and these effects did not depend appreciably upon seeing the movement of the target in depth nor upon change in the orientation of the subject's head relative to gravity.

1.2.4.1.3 Dark Adaptation

After exposure of the eye to a strong source of light, visual sensitivity decreases. Conversely in the dark the sensitivity of the eye to light increases dramatically over a period of time through the process of dark adaptation. Virsu and Vuorinen (1975) showed that perceived size diminished at low levels of background luminance. They concluded that dark adaptation is the primary source of these size effects. The main evidence for this conclusion was obtained from a demonstration that the same background luminance produced either an increase or a decrease in perceived size, depending on the adaptational state of the eye.

1.2.4.1.4 Eye/Head Elevation

As early as 1899, Zoth carried out experiments in which luminous milk glass bubbles were viewed both horizontally and vertically outdoors at distances ranging from 14 to 16.2 meters. The elevated objects were judged to be about twice the distance of the horizontal objects that were physically at the same distance as the elevated objects. Despite this observation about distance, Zoth concluded that the apparent size of an object was only affected when the object was at an essentially indeterminate distance. According to Zoth, this change in apparent size was mediated by convergence impulses and was not the result of a change in perceived distance.

Taylor and Boring (1942) suggested that elevating the eyes to view an object (e.g. the zenith moon) resulted in "excyclorotation", and compensatory vergence movements to null this cyclotorsion resulted in a diminution of the size of the object.

Enright (1989c) demonstrated that downward saccades for equidistant targets involved intrasaccadic convergence; and that upward saccades were followed by a pupil response that implied near-triad activation, presumably to compensate for intrasaccadic divergence. These vergence changes were apparently due to muscular constraints of the kind envisioned by Zoth (1899). This phenomenon was referred to as the primary consequence of vertical saccades. Immediately after upward saccades, near-triad processes were activated to maintain or restore the pre-saccade vergence state, activation of a kind that would lead to nearer accommodation and to shrinkage in apparent size.

However, Kaufman and Rock (1989), in their moon illusion discussion, were not convinced that elevating the eye to view an object (i.e. the moon), caused the apparent size of an object to change by any significant amount in comparison to when the object was viewed at eye level. Rock and Kaufman (1962) described an experiment in which the zenith moon was viewed either with eyes elevated or with the eyes level. The illusion ratio was 1.46 for eyes level and 1.48 for eyes elevated, and the difference was not significant. They concluded that the eye elevation alone was not a sufficient condition to produce an appreciable illusion. However, the possibility remained that

under natural conditions of viewing the moon against the sky, eye elevation was a necessary condition, if not a sufficient condition.

1.2.4.1.5 Binocular Versus Monocular Viewing

Holway and Boring (1941) noted a difference between monocular and binocular size matches. The monocular size match appeared slightly smaller. An essentially similar pattern of results was reported by Roscoe (1984); significantly less magnification was required for same-distance judgements when the standard scene was viewed monocularly.

It has been suggested that the fact that distant objects appear smaller when viewed with one eye than with two may be associated directly with an inward shift in accommodation that occurs when one eye is closed. (Roscoe, Olzak and Randle, 1975; Roscoe 1985) It is hypothesised that the closed eye tends to return to its dark focus or resting accommodation distance (Leibowitz, Hennessy, and Owens, 1975), and to draw the open eye inwards by the same amount (Roscoe, 1979). This seems unlikely, since there is little difference between the static accommodation response/stimulus curve recorded with binocular viewing and with one eye occluded. (e.g. Ramsdale, 1979) An experiment to compare accommodation during binocular and monocular viewing. will be discussed in chapter 3.

Enright (1989a,b) offered another explanation. He suggested that the resting state of vergence for an observer looking at an object with only one eye could typically involve convergence (esophoria). Opening the other eye as well would then typically lead to near-triad activation, to produce divergence, accompanied by increase in apparent size. In principle, the fusional centre might then take over control of vergence, permitting near-triad relaxation; and if the accommodative state resulting from the divergence demand were to produce significant image blurring, such "rezooming" would be expected. The evidence that most subjects do indeed perceive size increases when going over to binocular viewing can be interpreted as evidence that at least some magnification (larger size associated with divergence) persists, supplementary to the level during monocular viewing.

1.2.4.1.6 Retinal Disparity

When both eyes fuse an image of an object in a three-dimensional space, the image falling on each retina is slightly different. This slight difference in the retinal images is known as retinal disparity. Horizontal retinal disparities produce stereopsis; vertical disparities do not.

Wheatstone (1838, 1852) showed that this difference (i.e. stereopsis) contributes to depth perception. As a depth cue, retinal disparity is more effective at close than at great distances. The lateral separation between the 2 eyes for adults is about 65mm, and this provides a relatively small base for detecting angular differences. However, it is considered that stereopsis provides useful depth information up to about 450m (Davson, 1980)

A person with good stereopsis can judge depth better and thus enhance the accuracy of size/distance perception. If a person views an object monocularly, he/she has no stereopsis. This leads to poorer depth judgement and thus less accurate size/distance perception.

1.2.4.1.7 Stretching of retina during accommodation

Moses (1987) found clear evidence that the anterior human retina stretched during accommodation. If the stretch was largely confined to the region of the ora-serrata, its contribution to changes in space perception would be much less than if the central retina was distorted.

However, Blank and Enoch (1973) and Enoch (1975) had shown a perceptual effect involving accommodation-dependent distortions in the visual field due to differential stretching of the central retina. Hollins (1974) argued that the central region of the human retina stretched substantially by some 4.5% during marked (9.0 dioptre) accommodation.

The stretching of the central retina during accommodation means that the receptors move farther apart while the size of the optical image on the retina remains constant. This means the optical image covers fewer receptors, which could result in a change in size/distance perception. Presumably either the size might appear to be reduced (at the same distance) or the distance might appear to be increased (same size). Since the retina must remain fixed

near to the optic disc, stretching and any associated changes in space perception, will differ in the nasal and temporal fields, as found by Blank and Enoch (1973) and Enoch (1975).

1.2.4.2 Non -Ocular factors

Non-ocular variables which affect size/distance judgement include performance of cognitive tasks, type of instructions, pictorial cues and motion parallax.

1.2.4.2.1 Performance of Cognitive Tasks

Tasks that involve high levels of risk, uncertainty, or difficulty may induce a variety of internal states (e.g. stress, arousal, high demands on cognitive-processing capacity) which trigger physiological changes that directly affect visual perception. It has already been shown (section 1.2.4.1.1) that the apparent size diminishes as accommodation increases and vice versa (e.g. McCready, 1965; Komoda and Ono, 1974; Roscoe, 1985 and Meehan, 1995) Thus any change in accommodation resulting from performing cognitive tasks will result in a change in perceived size.

Gawron et. al (1985) and Malmstrom et. al (1980) suggested there were an outward shifts in accommodation when their subjects performed complex mental transformations and viewing a near target. In the Malmstrom et. al (1980) experiment, the subjects focused on a steady target and performed a secondary backwards counting task. The target presented was a black "x" and subtended a constant visual angle of 2.9 deg. The target was presented under three separate constant-focus conditions, 0.0D (far), 3.0D (near), and open loop (indeterminate distance). The secondary task was a paced, backwards counting, written task. Figure 1.4 shows the results found

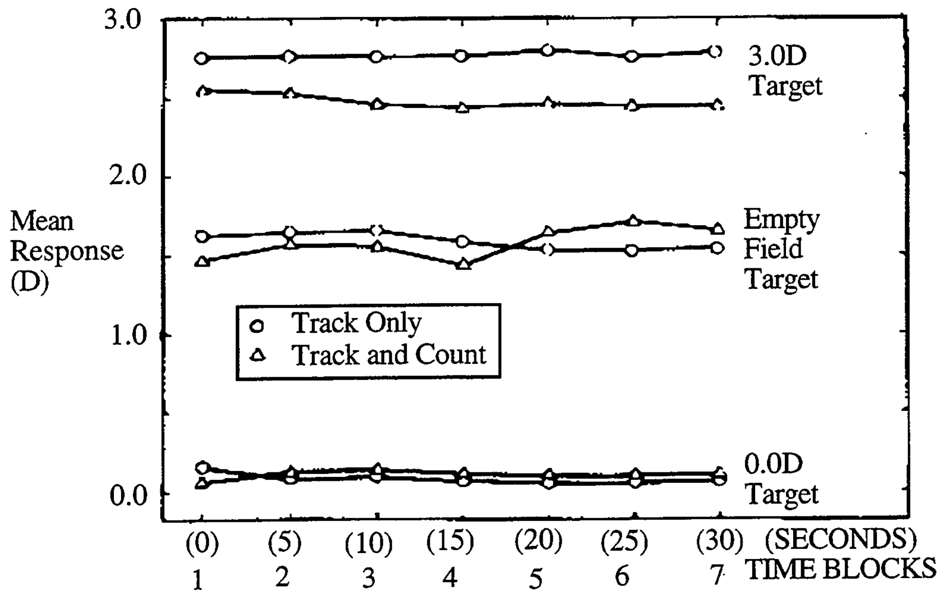


Figure 1.4: Concurrent counting task. Mean accommodation response plotted as a function of task and target distances; N = 5 (Malmstrom, et al.; 1980)

Their results showed that there was a significant outward shift in accommodation away from the 3.0D (near) target during concurrent counting task.

Randle et. al (1980; cited by Malmstron et. al, 1980) examined 20 comercial pilots who were required to make several task-related decisions during a simulated night-landing task while viewing the display through various magnifications. Their results suggested that the importance of the decision appeared to influence the accommodative state of the pilot. Each cumulative flight decision caused a small (about 0.1 dioptre), but persistent, accommodative shift, always towards the visual far point.

Gawron et al. (1985) hypothesised that such outward shifts in accommodation may be associated with performance of tasks that involve distant targets (e.g., other aircraft in the surrounding airspace) and/or require complex mental transformations (e.g., predicting the future position of an intruder aircraft relative to the pilot's own aircraft). However, we are not convinced that such an outward shift in accommodation is possible when the pilots are already viewing distant target (i.e. already accommodating at 0.0D) while flying.

1.2.4.2.2 Pictorial Cues

Pictorial cues may be seen when observing a 2-dimensional representation, such as a photograph or a painting. These cues are monocular, and are perceived just as strongly when viewed with one eye as when viewed with both eyes. The sense of depth that can be created by these cues is substantial. Artists are very sophisticated at manipulating the pictorial cues to create a sense of depth. Pictorial cues include the following:

i. Size of familiar objects

The perceived sizes/distances of familiar objects are often determined by the retinal image sizes they produce. If 2 objects are assumed to be the same size and remain constant in size, the object that produces the smaller retinal image size is assumed to be farther away. Ittelson (1968) hypothesised that the 2 assumptions are based on past experience; " *that they are some kind of weighted summation of what has been most often experienced under conditions where the functional indications ('cue') of the distance of objects was their relative apparent size.* "

ii. Brightness

The relative brightness of objects provides an indication of their relative distances. Brightness provides depth indication: the brighter object appears nearer and a dimmer object appears farther.

iii. Linear Perspective

Linear perspective is a specific type of size cue to depth. Figure 1.5 provides an example of linear perspective.

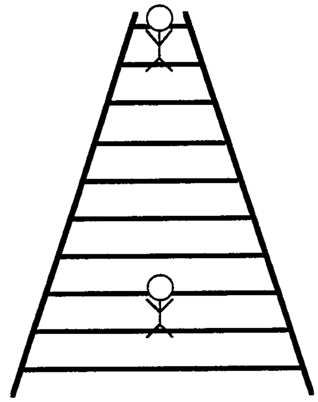


Figure 1.5: An example of linear perspective acting as a monocular cue to depth

A strong sense of depth is perceived because it is assumed that the horizontal lines on the bottom of the picture and those at the top of the picture are the same size. Because the lines at the top of the picture are seen as smaller, it is assumed that they are farther away. It is also assumed that the 2 longer lines (vertical lines) are parallel. If this were the case, the reason that they appear closer together at the top of the picture is that they are farther away. Linear perspective can also affect size estimates. The man near the top is perceived as bigger than the man below even though their real sizes are the same.

iv. Texture Gradient

This cue combines some of the aspects of relative size and linear perspective. Basically it may be described by noting that regions in the field in which objects or visual elements are more densely packed together seem to be farther away.

v. Interposition

Interposition occurs when one object blocks the view of another object. The result of this interposition is that the blocked object appears farther away from the observer than the object that does the blocking. Interposition provides one of the strongest indications of relative distance and thus affects perceived size and distance.

vi Familiarity/ Past Experiences

Familiarity of objects also plays an important role in the perception of size and distance (e.g. Leibowitz and Heisel, 1958; Hanely and Zerbolio, 1965; Leibowitz and Judischr, 1967 and Farquar and Leibowitz, 1971). The more familiar the person is with the objects, the greater the role that size constancy plays in size/distance perception.

vii Clarity/Aerial Perspective

Clarity is essentially a form of interposition. Objects in a photograph or picture that appear clear are interpreted as being nearer than those objects that appear hazy. Fog, smoke, and rain act as interposing elements that contribute to making the obscured objects appear farther away.

viii. Lighting and Shadow

When light falls on an object, the object casts a shadow. The shadow is interpreted as falling behind the object. Consequently, a sense of depth is created.

1.2.4.2.3 Motion Parallax

In everyday observation we are constantly in motion - standing up, turning around, walking, sitting down: very rarely do we look at completely stationary objects for any length of time. As one moves about, the positions of objects change in a manner relative to the objects' "objective" distances from the observer. Their relative movement provides an indication for the distances one perceives.

By definition, motion parallax is a kinetic monocular depth cue that refers to the relative motion of two objects.

1..2.5 Perceptual Awareness versus Actual Environmental Conditions

After this discussion of all the individual factors which affect size/distance judgement, their combined effect on the correspondence between perception and the actual environment.

Correspondence means sufficient agreement between perceptual awareness and the environment condition to provide a reliable prognosis for effective action under particular circumstances.

From the point of view of effective behaviour, it is apparent that in general some factors (cues) are more reliable than others. For example overlay cues are more reliable than size cues, and size cues are more reliable than brightness cues (Ittelson, 1968). The greatest reliability is found when the greatest number of cues supplement each other. For example, when there are overlay, size and brightness cues which supplement each other, perceptual awareness is more reliable than when there are only brightness cues (Ittelson, 1968).

It is also evident that an individual's perceptual awareness is the product of a taking account of all the immediately existing cues and indications and weighting them on the basis of the reliability of the assumptions on which they are based. In normal conditions, a great many different cues and indications are taken into account. These may supplement each other or be in conflict, the more reliable cues and indications may dominate and the less reliable be given no weight, or both may be given more or less weight (Ittelson, 1968).

The resulting percept may be in effective correspondence with the environmental conditions or it may be in partially effective correspondence. If the percept corresponds perfectly with the environmental conditions, the law of visual angle might be expected to apply (i.e. the perceived size of an object is determined entirely by the optical image size on the retina, and the retinal image size is determined by the visual angle of the object). Nevertheless, in a natural environment, this does not happen. For example, a person at 6 meters does not suddenly appear to double in size when he/she walks 3 meters towards the observer. Size constancy also plays an important role.

1.3 Looming (changing size)

In a dynamic viewing environment, the sizes of the retinal images keep on changing. For example, if a plane is flying towards a big patch of cloud from a far distance, the change in the dimensions of the retinal image of the cloud will be much more significant than the change in its vergence. Such looming of the cloud (or other

objects in the line of sight of the pilot) may affect the pilot's ocular accommodation and hence perceived distance and size

Ittleson and Ames (1950) reported that target size could influence the accommodative response, presumably via the process of size-distance constancy. Alpern (1958) and Morgan (1968) failed to confirm this accommodative effect, but did find a proximal effect for vergence. Apparently, proximal vergence is taking place without a concomitant change in accommodation.

Kruger and Pola (1985, 1986 and 1987) showed that changing size was an effective stimulus for accommodation and was involved in accommodative control. Accommodation was affected because of the changes in apparent distance of the target as a result of the changes in the target's size. Leon et al. (1988) showed that changing size was stimulating accommodation directly and vergence secondarily through an AC/A crosslink.

Kruger and Pola (1987) in their experiment with 4 subjects showed that if the stimulus dimensions were changing sinusoidaly with time at lower frequency, the target distance remaining constant, the amplitude of response was higher. Figure 1.6 shows the accommodative responses of their 2 subjects when the stimulus was changing at 0.05 Hz in an open-loop condition. The stimulus was a Maltese cross which angular size varied between 2 and 6 deg.

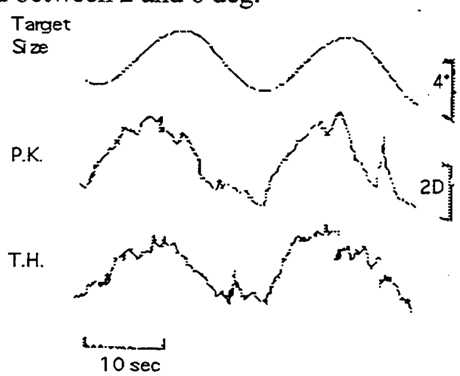


Figure 1.6: Accommodative responses of two subjects (T.H.) and (P.K.) at 0.05Hz during the size-only condition. The responses of these subjects were often as large as 2 or 3D (Kruger and Pola ,1987)

Figure 1.7 shows the accommodation responses of one of their subjects, B.F. to the size-only condition at four temporal frequencies. As the frequency of the stimulus increased the accommodative response followed at the same frequency. The

amplitude of the response was about 0.5D at the lower frequencies and decreased to about 0.25D at 0.8 Hz

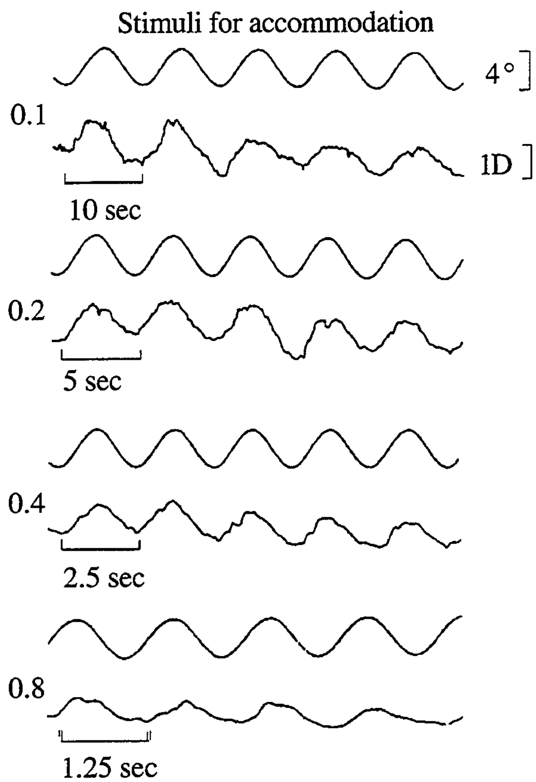


Figure 1.7: Accommodative responses of subject B.F. at four frequencies (0.1, 0.2, 0.4 and 0.8 Hz) during the size-only condition. At each frequency the top trace is the stimulus and the bottom trace is the accommodative response. As the frequency of the stimulus increased the response followed at the same frequency (Kruger and Pola, 1987)

Thus the above authors (Ittleson and Ames, 1950; Kruger and Pola, 1985, 1986 and 1987; and Leon et al., 1988) showed that an increase in the size of a target with no change in distance will result in an increase in the accommodative response. This increase in the angular subtense of the target at a fixed distance was apparently interpreted as the approach of a target of fixed size.

However Takeda and Fukui (1994) found a different result. They used the three-dimensional optometer (TDO III) to measure accommodative responses when gazing at a spotlight that changed its diameter in a completely dark room. The spotlight was placed at 33 cm (-3.0D) from the subjects. The size of the smallest spotlight was 3 mm (0.7°) and the largest was 30 mm (6.9°). The target was viewed under

monochromatic red light and luminance was 0.6 cd/m^2. The size of the target was varied in two ways:

(1) stepwise (dark to small to dark to large to dark) and

(2) rampwise (dark to small to large to dark).

The smallest and largest spot sizes were presented for about 5 - 9 sec. The time span was roughly 10 sec.

Though the subjects felt that the spotlight approached them when its diameter was bigger, the magnitude of accommodation when viewing the smaller diameter spotlight was greater than that for the larger diameter spotlight. (See figure 1.8)

Figure 1.8a

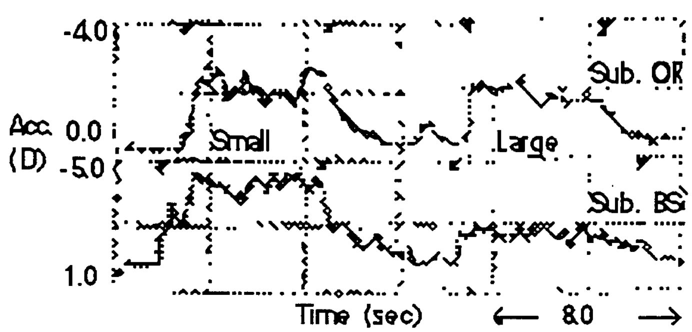


Figure 1.8b

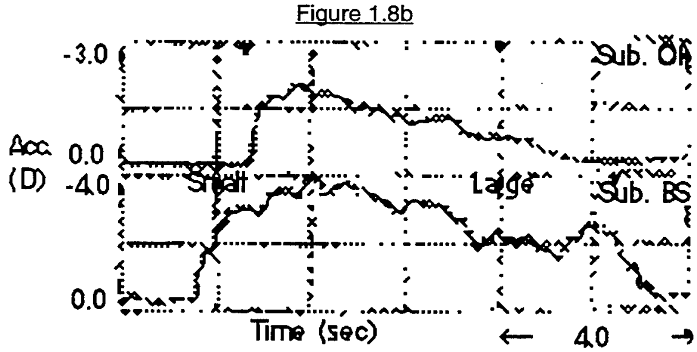


Figure 1.8: (a) Accommodation response of subject OR (upper) and subject BS (lower) for the step change (small, large) of spotlight diameter gazing at its centre. (b) Accommodation response of subject OR (upper) and subject (lower) for the ramp change (small to large) of spotlight diameter when gazing at its centre. (Takeda and Lida, 1994)

The average increases in accommodation when their 3 subjects viewed the smaller diameter was 1.2D for step change and 1.05D for ramp change of the diameter of the spotlight. The investigators inferred that this phenomenon came from the effort to

reduce the accommodation lag dynamically in order to see the smaller target more clearly.

It is not appropriate to compare the results of Kruger and Pola (1987) with the Takeda and Fukui results for the following reasons:

(1) The stimuli differ

Kruger and Pola used Maltese Cross as target which allowed more precise foveal fixation. Takeda and Fukui used a circular spotlight. The images of most of the edge of the larger spotlight fell on the peripheral retina as compared to Maltese cross, hence the spotlight constituted a less effective accommodative stimulus.

(2) Opened/closed loop condition

Kruger and Pola's experiments were done in an open loop condition to remove the negative effect of blur on accommodation. Takeda and Fukui conducted their experiments in a closed loop condition, as would apply during real-world viewing

(3) Variation in temporal frequency

Kruger and Pola used sinusoidally-changing stimuli while Takeda and Fukui used step and ramp changes. Sinusoidal input produces a great deal of anticipation in subjects, as admitted by Kruger and his colleagues. The nature of this predictive control makes it difficult to compare the 2 results.

1.4 The eye's response to aniso-accommodative target

As mentioned in section 1.1.3, maladjustment of VR systems may result in unequal stimuli to the accommodation of the 2 eyes.

It is a classic view that the two eyes always accommodate equally and observed behaviour reflects the system's varying choice between which eye is blurred. Campbell (1960) measured the correlation of accommodation between the two eyes and found that the refractive powers of the two eyes were very similar when the subjects viewed binocularly a small, high contrast object placed at 50 cm. Clark and

Crane (1978), and Heron and Winn (1989) also found the accommodation response of the two eyes behaved in a highly synchronous manner. They concluded that this was because the origin of binocular accommodation occurred at or above a point where the two third cranial nerves are functionally conjoint.

1.4.1 Unequal accommodation in abnormal eyes

Unequal accommodation may result from a variety of factors.

It may be caused by unequal action of the ciliary muscles. Some pathological, physiological, and neurological anomalies in the muscles may result in the eyes of an individual accommodating differently. Cogan (1937) found an increased capacity to accommodate by 0.50D to 2.50D in the affected eye after surgical or other damage to the cervical portion of the sympathetic nervous system. This was the first comprehensive case put by Cogan that the ciliary muscle was innervated by the parasympathetic and sympathetic systems, though controversy remains. Ophthalmoplegia interior due to syphilis, third nerve palsy, trauma, or toxins may affect one eye more than the other, thus resulting in unequal accommodation.

Unequal rigidity of the lens in the eyes could also result in unequal accommodation. This could happen in early presbyopia where sclerotic changes to one eye advanced faster than in the other.

Drugs affecting the ciliary muscle will also affect accommodation. Cycloplegic drugs (antimuscarinic agents) such as atropine, cyclopentolate and tropicamide paralyse the ciliary muscle by blocking the muscarinic receptors normally stimulated by the release of aceteylcholine from the nerve endings of the parasympathetic system. (O'Connor-Davies et al., 1989). Frequent cases of unequal accommodation can also occur after binocular instillation of cycloplegia, a condition Beach (1942) called anisocycloplegia.

Parasympathomimetic drugs stimulate the ciliary muscle causing an increase in accommodation. (O' Connor-Davies, et al. 1989).

Sympathomimetic drugs such as 10% phenylephrine cause the eye to accommodate less (Mordi et al., 1986; Zetterstorm, 1984; Garner et al., 1983) although it is often wrongly said sympathomimetic drugs cause little or no

cycloplegia since they do not paralyse the ciliary muscle (e.g. Andres, 1976; Jose et al., 1984).

Thus monocular instillation of such drugs (antimuscarinic agents, parasympathomimetics, sympathomimetics) can cause the eyes to have unequal accommodation.

1.4.2 Unequal accommodation in normal eyes

Several authors in the past postulated that unequal accommodation can exist in normal eyes. Grimm (1933) managed to fuse 2 partly identical and partly fine targets in the state of artificial anisometropia (placing a spherical lens on one eye). Though accommodation was not measured at all, he convinced himself that the perfect fusion of the targets necessitated unequal accommodation. He claimed to be able to overcome a difference in refraction of 1.50D.

Stoddard and Morgan (1942) used negative spherical lenses to stimulate accommodation and a haploscope to measure accommodation. They reported that some individuals were able to exhibit 0.50D greater accommodation in one eye than in the other. but that the average ability to accommodate unequally was less than 0.12D.

Ball (1952) measured accommodation subjectively and objectively and used concave lenses to stimulate accommodation. In the subjective part of his experiment, the lenses were added gradually on one eye until the observer first reported a blur of the target seen by that eye. Then the concave sphere was reduced until the targets seen by both eyes were equally clear. The subjective experiment found that the average unequal accommodation was 0.21D. In the objective part of the experiment, retinoscopy was used to measure accommodation and the average difference in accommodation between the eyes was 0.11D. Both these figures are at the limit of the measurement technique used.

Rosenberg et al. (1953) used a specially constructed haploscope and stigmatoscopy to measure accommodation when the eyes converged asymmetrically. They concluded that unequal accommodation between the two eyes did exist under the condition of asymmetric convergence and that the eye closer to the target always accommodated more than the other.

More recently, Marran (1995) claimed that the visual system can respond to anisometropic stimuli in a head mounted displays due to design flaws with aniso-accommodation. Schor (1995) proposed that the eyes could simultaneously clear vision at 2 separate focal planes presented binocularly with suppression and differential accommodation. Marran and Schor (1996) suggested that aniso-accommodation is a non consensual accommodative response of the two eyes that can be stimulated experimentally with lenses, and is not the result of rapid monocular changes in accommodative state nor is it dependent on pupillary constriction.

1.5 The eye's response to virtual reality images

Interactive human/computer interfaces known as VR systems are a recent development in one of the areas of computer technology. Such systems enable the user to interact with the computer within a 3-D computer environment. Virtual reality systems are increasing popular in both vocational and recreational use. In the field of aviation, it is common to train pilots in a 3-D flight simulator environment.

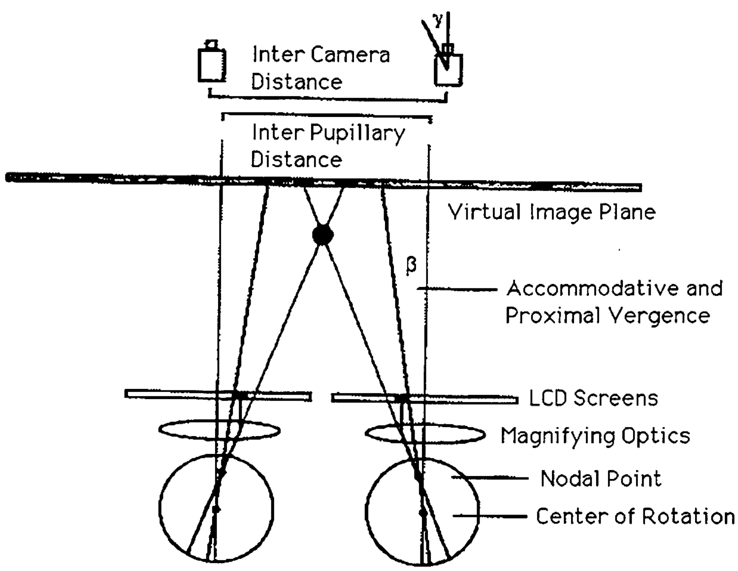


Figure 1.9: Stereoscopic design, and factors affecting spatial perception with a head-mounted display. Images presented on LCD screens are viewed through magnifying optics, which project two half images at a visual angle (a) and a fixed focal depth (virtual image plane). Fusion of these images will result in the percept of an object in front of, or behind the virtual image plane. The screen inter-camera distance, the inter-screen separation and the viewer's (b) will be induced by the focal depth of the screen images, but this will be independent of, and may conflict with, disparity driven vergence. Note the angle of the virtual cameras (g) will normally be zero, but some vergence may occur in tele-operated systems with remote cameras. Schematic layout, not to scale. (Wann et al., 1995)

VR systems engender the percept of a visual environment via computer generated, structured optic arrays. Stereoscopic depth may be introduced through the presentation of disparate images. Stereoscopic displays may be produced on conventional desktop computer screens by using polarising filters or anaglyphs and overlaying two disparate images, or by using shutter spectacles to time-multiplex the generated arrays. An alternative method of displaying computer generated images is to use a head-mounted display (HMD).

A HMD typically uses two liquid crystal display(LCD) screens, one in front of each eye, viewed through a simple lens system. (See figure 1.9). The screens are viewed through, for example, +36D compound lenses with each LCD placed close to the focal length of the compound lens. In newer virtual reality systems, adjustment of interpupillary distance (from 58 mm to 70 mm) and independent focusing for each eye are catered for in the headset.

The eyes face several problems in a virtual reality system:

1.5.1. Mismatch between Accommodation and Convergence

Under normal viewing conditions, accommodation and convergence vary synkinetically and are dependent on object distance. In contrast, within a VR system the eyes must maintain accommodation on the fixed LCD screens, despite the presence of disparity cues that necessitate vergence eye movements in the virtual scene (Wann et al., 1995). Thus, when wearing a stereoscopic HMD, the normal relationship between accommodation and convergence is disrupted. In a study by Edgar et al, (1993), the accommodation responses of 8 subjects to real and virtual images were assessed. It was found that the subjects tended to over-accommodate to the virtual images. This over-accommodation can be explained by the vergence movement the eyes have to make in response to a disparity virtual image. This will be more evident in large disparity displays (Wann et al., 1995). See figure 1.10. Such vergence movements would normally be accompanied by vergence driven accommodation through the cross-coupling of accommodative vergence (conventionally expressed as the CA/C ratio and the AC/A ratio).

Noro and Kawai (1995) showed that, in general, after a period of viewing the 3-D display, far-to-near accommodation response times increased, presumably due to fatigue. This increase in response time became progressively greater when the

disparities exceeded about 2 degrees, implying that the fatigue was due to the breakdown of the normal relationship between accommodation and convergence.

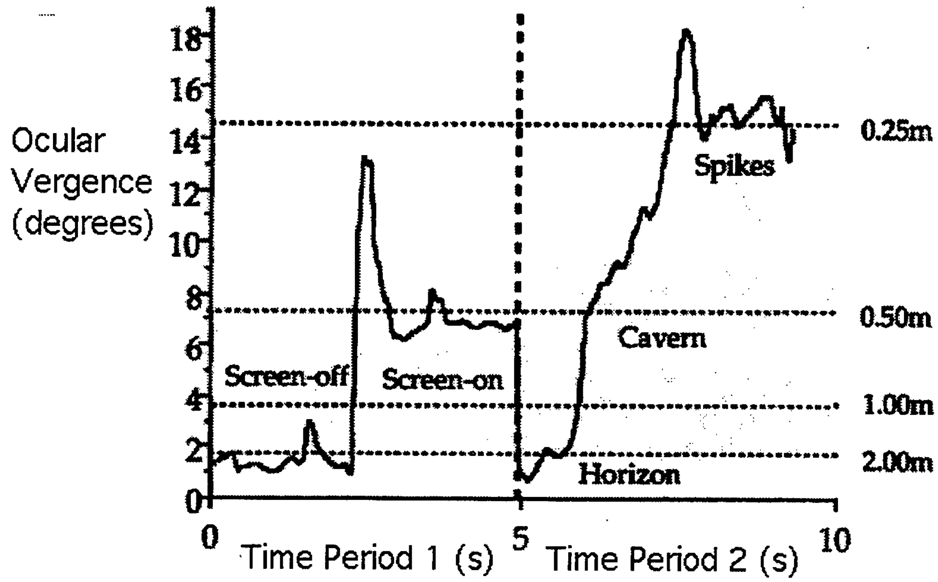


Figure 1.10: An illustration of vergence eye movements in response to a virtual display recorded with infra-red limbus tracking during the use of a HMD. During Time Period 1 a participant wore the HMD, but the screens were extinguished and the participant attempted to relax accommodation and convergence. When the screens were illuminated the participant's eyes converged to match accommodation. Time Period 2 displays vergence records for the participant travelling on a virtual roller-coaster ride. The participant rose to the top of a switch back hump and could only see distant objects ahead (Horizon). The display then "accelerated" the participant down a slope toward the mouth of a cavern, then into the dark and through a set of virtual spikes. The two peaks in Time Period 1 and 2 are artefacts of eye-blinks. Horizontal dotted lines indicate estimated depth for the point of convergence at different ocular angles. It can be seen that the participant does not passively sample the information, but responds to disparity cues in the virtual reality display by converging appropriately, despite conflicting accommodative stimuli (Wann et al. 1995).

1.5.2. Poor retinal image quality

The typical resolution of a LCD screens is usually low: 360 x 240 primary colour pixels equivalent to 208 x 139 RGB triads (Holloway et al, 1992; cited by Mon-Williams et al. 1993). To further degrade the image quality, the LCD based HMDs require that the screens are driven from a composite video signal which is

below the resolution available from most graphics processors. The resulting image displayed through many HMDs is of poor quality, with low level of illumination, poor contrast and with uncertain binocular alignment (Mon-Williams et al. 1993).

Robinett and Rolland (1992) estimated the users of a HMD (Eyephone Model 1) to be roughly equivalent to 6/60 when they viewed a virtual Snellen chart.

1.5.3. Lack of blur cues and close working distance

The computer generated optic array lacks the blur cues that arise in a natural viewing environment. It is accepted that blur is a stimulus to accommodation and this stimulus has received much attention (Campbell and Westheimer, 1960; Stark et al., 1965; Krishnan et al., 1973; Van der Wildt et al., 1974; Tucker and Charman, 1979). To put more strain on the accommodative system, the focal characteristics of the display are closer to those of a pictorial representation. One of the most commonly used HMD systems is the VPL Eyephone LX (Redwood, CA, USA) where the LCD screens are placed close to the focal point (2.78 cm) of a +36D compound lens. Such an arrangement means that a user must accommodate by 3D to produce a clear retinal image. Such a level of accommodation is likely to explain the esophoric shift experienced by users (Mon-Williams et al., 1993).

1.5.4 Proximal Accommodation and Convergence

Another response by the eyes to near working distances in HMDs is proximal accommodation and convergence. Jones (1995) showed that under open-loop conditions in a HMD, subjects revealed significant proximal accommodation and convergence to physically near targets that were at optical infinity. However, proximal effects did not have a significant effect on the accuracy of accommodation or convergence when the pupil size was 3 mm or greater. It was concluded that such proximal effects may be avoided in a HMD by utilisation of exit pupils sufficiently large as to encompass a natural pupil.

1.5.5. Induced Prism

With such high powered lenses used in HMDS, even very small displacements of the screens relative to the lenses are liable to produce significant amounts of induced prism. (Prentice's rule: The prism power **P** prism dioptres produced by a decentration **d** cm of a lens power **F** dioptres is given by **P = cF**). The visual

system may respond to such prismatic demands by changing the resting position of vergence (i.e. by shifting the heterophoria). Rapid adaptation to any such induced prism is well within the visual system's capabilities (Henson and North, 1980; Henson and Dharamshi, 1982) but is likely to produce problems within the fusional system after prolonged adaptation. If too large a prism is placed in front of the eyes then the ability to cope with the prism will be reduced and this will result in abnormal binocular vision with related symptomatic complaints. (Sethi and North, 1987). What constitutes too large a prism varies from individual to individual (North and Henson, 1981) and between age groups (Winn et al. 1994). It has also been shown that individuals with binocular vision anomalies lack the ability to adapt to prisms (Henson and Dharamshi, 1982) and this has been hypothesized as being one of the causes of binocular vision problems (Schor, 1979).

It is possible to remove prismatic error by either physically changing the screen separation or, in a fixed screen system, by varying the inter-camera distance as a software parameter (Wann et al. 1995).

1.5.6. Unstable retinal Image

Under normal viewing conditions, the vestibular ocular reflex (VOR) generates compensatory eye movements that counter the effects of head movement and maintain a stable image on the retina. In an HMD, the same VOR may result in retinal slip and image degradation. Because the HMD moves with the head, VOR eye movements that compensate for head motion, result in a moving retinal image. This causes apparent image motion and reduced clarity. (Peli, 1995).

This problem can be overcome by having a head tracking device in the HMD that compensates for these movements. However, in many devices, such compensation is not included or is very crude. Even with better head tracking, delays in the display update may result in the retinal image slipping and image jumpiness or blurring during motion. (Peli, 1995)

In addition to their potential effects on image quality, conflicts between vestibular and visual inputs are considered to be common causes of motion sickness. Visual scene motion without corresponding vestibular input, as is commonly the case in flight simulators, can result in motion sickness. Such illness was reported to occur

in almost 50% of pilots tested on the first day of training, but the magnitude of illness decreased on subsequent days (Uliano et al., 1986; cited by Peli 1995).

In the following chapter, the effects of accommodation on size/distance perception will be discussed in more detail.

CHAPTER 2: ACCOMMODATION AND SIZE/DISTANCE PERCEPTION

2.1 Introduction

It has long been known that when an object subtending a fixed angle at the eye is observed, the apparent size diminishes as either the accommodation or convergence of the eyes is increased (e.g. Wheatstone, 1852; Von Kries, 1924; Grant, 1942; Woodworth and Schlosberg, 1954; McCready, 1965; Komoda and Ono, 1974, Benel, 1979; Iavecchia, Iavecchia and Roscoe, 1983). Wheatstone in his "Contributions to the Physiology of vision, part the second", described the effect of vergence changes on the apparent size of observed objects: *"When an object is viewed binocularly and convergence of the eyes is forced to change (as can easily be arranged by use of mirrors or prisms), a conspicuous change is perceived in the apparent dimensions of the observed scene and its contents. Convergence causes a shrinkage in size, divergence an enlargement."* The phenomenon has been named convergence micropsia and it has been quantified (Heinemann and Nachmias, 1959; Enright 1989a,b). Enright in his experiment was able to reduce the size of the horizon by 30% when viewing binocularly (1° change in vergence) as compared to monocularly. He concluded that the size reduction reflects convergence micropsia. (i.e. 1° change in vergence evoked 30% reduction in apparent size.)

Nevertheless, the question of whether convergence or accommodation, or more probably their interaction, is the primary mediating mechanism has not been resolved. Investigators have attempted their independent manipulation, with the object of discovering whether one or the other is solely responsible for the effect, but the results are inconclusive because interaction effects are suppressed or concealed in reduction experiments. However, research in which accommodation has been measured while observers performed meaningful visual tasks shows that myopia and micropsia are still present when images are collimated, thereby eliminating near-field convergence (Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1988; Norman and Ehrlich, 1986).

Where accommodation alone is involved, this effect is known as *accommodative micropsia* (Alexander, 1975; Hollins, 1976). This phenomenon has been invoked by Roscoe and his colleagues. (e.g. Roscoe, 1979, 1984, 1985, 1987;Hull et al, 1982; Norman and Ehrlich, 1986; Iavecchia and Iavecchia, 1988) as a possible explanation of

a variety of inappropriate judgements of the size or distance of objects which typically involve errors of up to 40% (Roscoe, 1984; Meehan, 1990). They hypothesise that this error of judgement of the size or distance of objects arises as a result of the error in accommodation when the accommodation system returns to its dark focus.

There are at least five potential reasons why accommodative micropsia might occur:

1. The retinal image of an object of constant subtense becomes smaller as the eye accommodates, as a result of the purely optical changes in the form of the crystalline lens.

2. If accommodation is induced by placing negative lenses in front of the eye, the retinal image is reduced in size by the minifying effect of the lenses.

3. Although the optical image remains the same size, the projection onto the neural retina changes during accommodation as a result of transverse changes in the dimensions of the retina due to tractional forces associated with the act of accommodation. To give micropsia the retina would have to stretch so that a retinal image of constant dimension covered a smaller array of receptors. There is some evidence that this occurs (Blank and Enoch, 1973; Enoch, 1973, 1975; Hollins, 1974; Miles, 1975).

4. The size changes arise at higher levels of the neural system, the size scaling being influenced by inputs from the accommodation and vergence systems (Holst and Mittelstaedt, 1950; Richards, 1967; Marg and Adams, 1970; Hochberg, 1972). Such scaling takes into account all stimulus conditions including the distance at which the eyes are accommodated. This information is presumably in the form of signals from the oculomotor systems that control accommodation and convergence. Von Holst (1957) (cited by Enright 1989b, In Moon Illusion pp 83) carried out the following experiment: If one eye is covered and a paralytic drug (atropine) is applied to the viewing eye so that no accommodation response by the lens of the eye is possible, one can shift attention from a far to a nearby object along the line of sight and thereby evoke micropsia. von Holst interpreted this result as indicating that the micropsia must arise in conjunction with "command signals" sent to the ciliary muscles in the attempt to accommodate for near vision because "absolutely nothing happens in the periphery." The conclusion that "nothing happens" is, as it turns out, mistaken; in this

experiment, the covered eye can be expected to converge, as an expression of "proximal vergence" (Hokoda and Ciuffreda, 1983), and one would also expect changes in the configuration of extraocular muscle forces acting on the viewing eye (Enright, 1980, 1984). Von Holst's experiment is due only to central processing of a corollary discharge associated with "command" signals. Peripheral correlates do exist, meaning that the processes underlying micropsia may be more accessible to study than if cortical command signals alone were responsible for the perception.

5. The misjudgement arises at a still higher level of the visual system and involves relatively subtle psychological factors, such as the various effects discussed by Ittelson (Ittelson, 1952, 1968). Such effects are, however, highly dependent on the nature of the stimulus, its surround and other conditions (Hochberg, 1972).

2.2 Accommodation-dependent changes in the size of the retinal image

There are 4 potential accommodation-dependent changes in the size of the retinal image, they are:

2.2.1. Size changes associated with the use of small artificial pupils and errors of focus.

If a small pinhole is placed in front of the eye, the depth-of-focus is considerable and the retinal image will become more distinct. Suppose an object is held closer to the eye than the near point (the eye under-accommodates), the increase in the depth-of-focus will enlarge the retinal image. This is because the aperture stop is no longer the pupil of the eye but rather the artificial pupil. As a result, the new chief ray is displaced outwards with respect to the original chief ray and the retinal image is larger. This apparent magnification increases with the distance between the artificial pupil and the cornea. (See figure 2.1a)

If on the other hand, a distant object is observed with the eye accommodated for near, insertion of the small artificial pupil results in a decrease in image size which is again proportional to the distance between the pupil and the cornea.(See figure 2.1b)

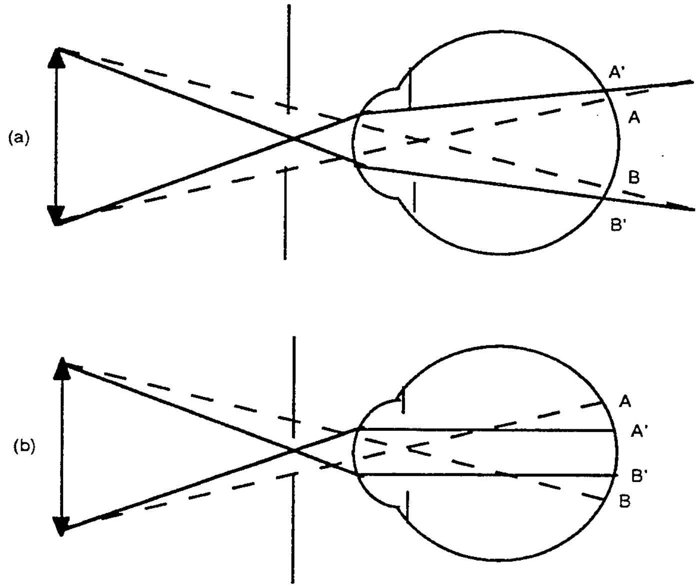


Figure 2.1: Effect of a small artificial pupil placed in front of the eye on the apparent size of an object when accommodation is in error. In each case the size AB of the retinal image with the natural pupil is defined by the dashed lines, representing the chief rays passing through the centre of the natural pupil, and the size A'B' of the retinal image with the artificial pupil is defined by the full lines, representing the new chief rays passing through the centre of the artificial pupil. (a) Near object, accommodation for greater distance (under-accommodation) object appears larger A'B' >AB. (b) Near object, accommodation for closer distance (over-accommodation), object appears smaller A'B' < AB

If the eye accommodates to the objects, the dependence of the image size on the pupil position disappears. This is because the diameters of the blur circles of each of the object points go to zero. All the rays from a given point on the object converge at the same point on the retina, so that the particular bundle of rays let into the eye by the pupil would go on the retinal plane.

Marsh and Temme (1990) have derived the following expression relating retinal image size to object size when the object is seen through a pupil forming an aperture stop for the eye:

$$h' = \frac{S'\,h}{n\,S}\left[(1 - d/Sa)/(1 - d/S)\right]$$

where:

h' = Retinal image size

h = Object size

S' = Image distance from the retinal image plane to the posterior principal plane of the eye

n = Refractive index of the final posterior medium of the eye

d = The distance between the artificial pupil and the anterior principal plane of the eye

S = Distance between h and the anterior principal plane of the eye

Sa = The distance between where the eye is accommodating and the anterior principal plane of the eye

Thus the retinal image size is affected by the object's position, the pupil's position, and the state of accommodation on the assumption that the chief ray determines the image of an out-of focus object. (See figure 2.2)

In normal viewing condition, (e.g. when a pilot is flying a plane) there is no artificial pupil, thus the qualitative effect on the retinal image will not be considered further here. Moreover, the size of the natural pupil should have no size effect on in-focus images (Biersdorf and Baird, 1966). However, the effect could conceivably occur with, for example, ocular viewing devices having small exit pupils,

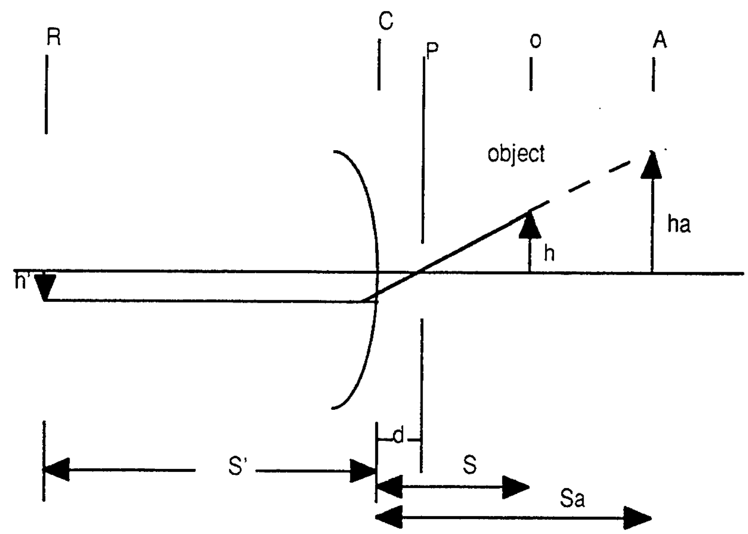


Figure 2.2: Object of size h at a distance S from the cornea. R = retinal image plane; C = anterior surface of the cornea; P = pupil forming the aperture stop; O = location of the object; A = plane of accommodation.

2.2.2. <u>Size difference between in-focus retinal images for an emmetropic eye at various levels of accommodation.</u>

There are 2 ways of calculating the size of in-focus retinal images of objects of constant angular subtense for an emmetropic eye at various levels of accommodation.

The first method suggests that there is a retinal image size increase when the eye accommodates for near objects as compared with distant objects of the same angular subtense.

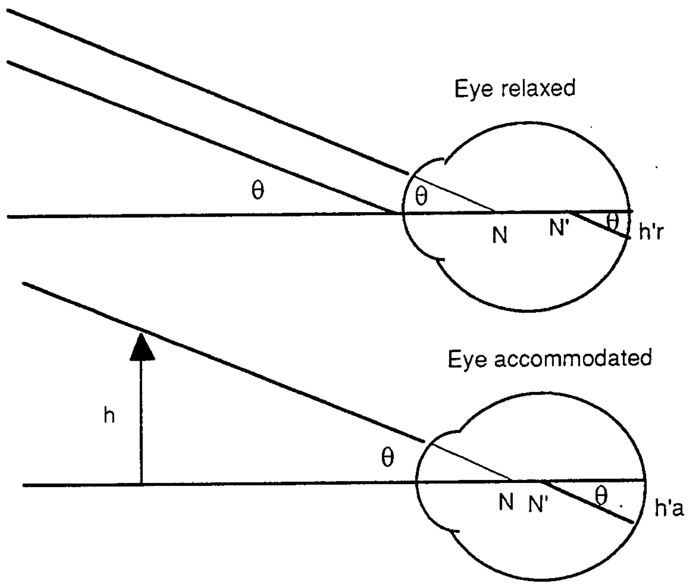


Figure 2.3: Change in the in-focus retinal image size (not to scale) for distant and near objects having the same angular subtense, q, at the first nodal point which does not move during accommodation. The second nodal point moves forward in accommodation thus causing h'a > h'r. (h'a = retinal image height of the relaxed eye, h'r = retinal image height of the accommodated eye)

Refer to figure 2.3. When the eye views the distant object with angular subtense of q, the retinal image height is h'r. As the crystalline lens changes its shape to facilitate view of objects of constant angular subtense at nearer distance, the second nodal point moves forward and causes a slight increase in the dimensions of the sharply focused retinal image, having a height of h'a. Pascal (1952) calculated a size increase of about 3% for a 8.50D of accommodation. Note, however, that this assumes that the subtense of distant and near objects remains constant as measured at the first nodal point (i.e. that the first nodal point does not move when the eye accommodates). Bennett and Rabbetts (1989) however say that the first nodal point moves with accommodation. This leads us to the second method of calculation. (See figure 2.4.)

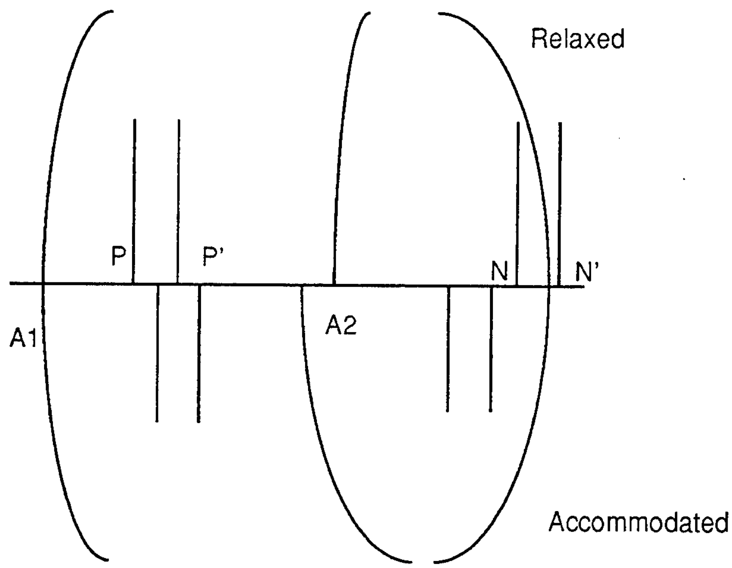


Figure 2.4: Comparison of the positions of the principal points P, P' and the nodal points N, N' of the Gullstrand-Emsley schematic eye in its relaxed (upper) and fully accommodated (lower) states.

The second method of calculation suggests that there is a retinal image size decrease when the eye accommodates for near objects rather than for distant objects of the same angular subtense. This occurs because if the subtenses and vergences of the objects are measured with respect to the centre of the cornea, the subtense of a near object at the first nodal point is less than its subtense at the cornea. The Gullstrand "exact" schematic eye predicts that there is a 2.5% reduction in the size of the retinal image with 8.50D of accommodation. (see also Le Grand and el. Hage, 1980) See figure 2.5. In practice the positions of the nodal points for any individual eye are not precisely known. Very often, experimentally the subtense and vergences of objects are measured with respect to the centre of the cornea since there is no practical problem in locating the cornea.

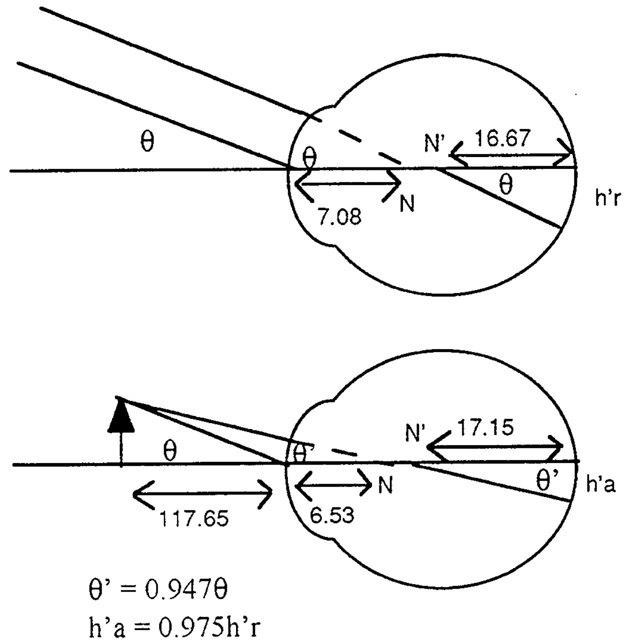


Figure 2.5: Change in the in-focus retinal image size (not to scale) for distant and near objects having the same angular subtense q at the cornea, using the relaxed and accommodated "exact" Gullstrand schematic eyes. It is assumed that the near object is at a vergence of 8.50D with respect to the cornea. Although on accommodation the nodal points move forward towards the cornea, the subtense q' of the near object at the first nodal point is smaller than at the cornea, so that the retinal image size $h'a < h'r$.

2.2.3. Size difference between in-focus retinal images for a corrected ametropic eye at various levels of accommodation.

When an ametropic eye is corrected for distance vision by a spectacle or contact lens, the so-called spectacle magnification produced by the lens (i.e. the ratio of the size of the image of a distant object in the corrected eye to that in the uncorrected eye) is :

$$\text{S.M.} = (1 - aFv)^{-1} \times (1 - [t/n]\, F1)\text{-}1 \text{, where}$$

a = vertex distance between the rear surface of the lens and the entrance pupil

Fv = Back vertex power of correcting lens

t = Lens thickness

n = Refractive index of lens

F_1 = Power of the anterior surface of the spectacle lens

The 2 right-hand terms are known as the power and shape factor respectively. When a near object is observed, in principle a 3rd factor, which Bennett and Rabbetts (1989a) term the proximity factor, comes into play. Bennett and Rabbetts show that the value of the proximity factor is approximately $(1 + a^2FvL)$ where L is the object vergence. With values of 'a' typically being about 0.015m, the proximity factor is generally negligible. Even high-powered lenses and close objects (e.g. a lens of back vertex power of -10.00D and object vergence L = -10.00D corresponding to an object at 10cm from the eye) would only yield a proximity factor of 1.023 x i.e. a size change of about 2%.

Other than the spectacle magnification which affects perceived size in a corrected ametrope, the ocular accommodation also plays a role. It is noted that a corrected hyperope of a given spectacle correction will have to accommodate more to see an object at a certain near distant, than a corrected myope having the same spectacle correction (of opposite sign) and an emmetrope for the same near object distance. (i.e.. $\text{HYPEROPE}_{(sp)} > \text{EMMETROPE} > \text{MYOPE}_{(-sp)}$) This is due to the effectivity at the eye of the vergence emerging from the spectacle lens as well as the difference in vergence of these pencils. (Obsteld, 1978 pg 147 - 152) (e.g. The ocular accommodation with a +8.00D spectacle correction of 12mm vertex distance for an object situated at 10cm from the spectacle point is +10.80D. The ocular accommodation with a -8.00D spectacle correction of similar vertex distance and object vergence is -7.49D. The ocular accommodation for an emmetrope to view an object 11.2cm (10cm + 12mm) from the cornea is +8.93D).

Due to the spectacle magnification (<1) produced by the negative lens in a spectacle corrected myope, the perceived size of a near object is smaller than for the emmetrope and the spectacle corrected hyperope viewing the same near object. However, the reduction in ocular accommodation in a spectacle corrected myope

may reduce the effect of accommodative micropsia and hence counter the minification of perceived size.

2.2.4. Accommodation-dependent size changes for out-of-focus images with an emmetropic observer.

As pointed by various authors, the situation in accommodative micropsia does not involve sharp images of objects at different distances (Marsh and Temme, 1990; Smith et al., 1992).

It essentially involves changes in the perceived size of the same object at a fixed distance when viewed with different levels of accommodation. Hence, in general, the associated retinal images will be blurred. Marsh and Temme (1990) use the following equation to calculate the magnification of a retinal image size of a distant object when the eye accommodates:

$$m = ha'/hr' = (1 + d/Sa), \text{ where}$$

m = magnification

ha' = retinal image size when the eye accommodates

hr' = retinal image size when the eye's accommodation is 0

d = distance between the entrance pupil and the front principal plane. It is assumed to have a fixed value of -2mm. (i.e. the 1st nodal point does not move forward when the eye accommodates)

Sa = distance from the front principal plane to the plane where the eye is correctly focused or accommodated.

Using a Gullstrand schematic eye as a reference (they did not state which one), they show that the retinal image size of a distant object increases with increasing accommodation, achieving a 1% increase in size at about 5.00D and a 2% increase in size at 10.00D of accommodation. This is consistent with the calculation of Charman (cited in Enoch, 1975) and the photographed retinal images of Heinemann (1961). This calculation is not, however, consistent with Roscoe's Zoom-lens hypothesis (Roscoe 1985). According to the Zoom-lens hypothesis, the apparent

size of the object decreases with increasing accommodation. Moreover the magnification calculated by Marsh and Temme (1990) required a 5.00D change in accommodation to yield a 1% change in image size, whereas the Zoom-lens hypothesis requires about 20%-40% change in image size with a change of only 0.50D accommodation.

Smith et al. (1992), taking into account that the anterior principal plane moves forward with accommodation, derive the following equation:

$m = (S'/So')\ (1 + e/S)$, where

m = magnification of the retinal image

So' =the distance between the back principal plane and the retina for the relaxed eye

S' = the distance between the back principal plane and the retina for the accommodated eye

S= the distance from the front principal plane to the plane where the eye is correctly focused or accommodated

e =the distance between the front principal plane of the eye and the entrance pupil for the accommodated eye

Using this equation, Smith et al. calculated the magnification of 4 schematic eyes associated with various accommodation levels. See figure 2.6.

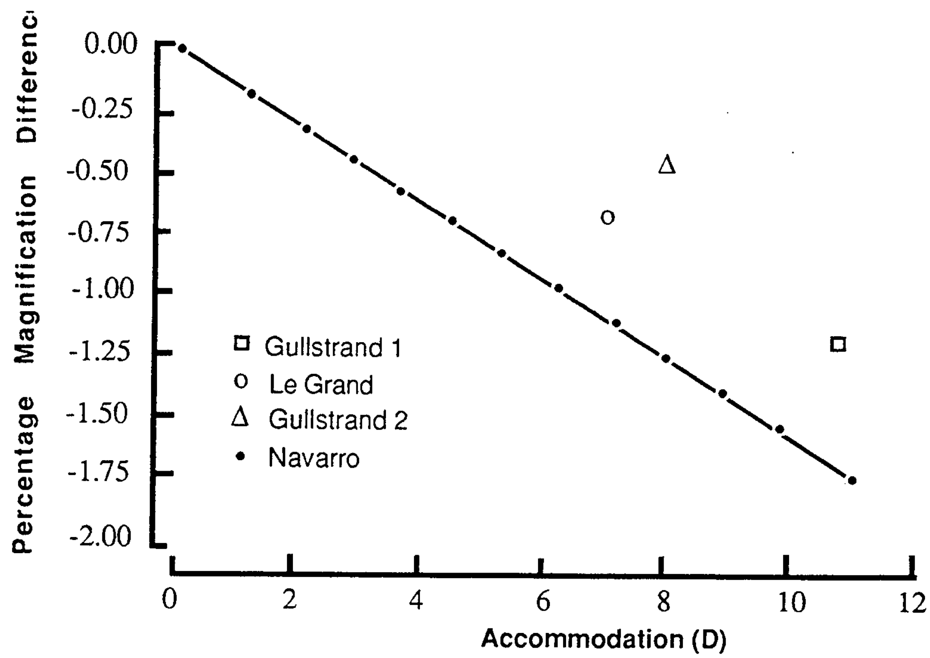


Figure 2.6: Percentage of retinal image magnification attributable to accommodation at various accommodation levels. The percentage magnification is defined as (actual magnification - 1) x 100

They concluded that the retinal image size of a distant object decreases in size when the eye accommodates. They calculated the magnitude of this diminution for four schematic eyes ranged from unity at infinity to a maximum of 0.98 (-2%) at about 12.00D. For distances at which accommodative micropsia is typically observed (about 2.00D), retinal minification is less than 0.997 (-0.3%)

2.3 Comparing the Accommodation-dependent changes in the retinal image size with the observed reduction in perceived sizes

After considering the 4 situations, the change in the size of retinal image as a result of accommodation is negligible as when compared with the observed reduction in apparent sizes of objects viewed in an imagery display or the moon illusion. Values for the former have been shown to vary between 21% and 33% (Roscoe, 1984) and between 3% and 11% (Meehan and Triggs, 1988). These values have been shown to vary widely according to the prevailing set of viewing stimulus conditions (Meehan, 1990).

Thus the accommodation-induced reduction in the sizes of retinal images is likely to be almost negligible for the accommodation errors that are observed in many studies.

(e.g. Iavecchia, Iavecchia, and Roscoe 1988). Even if all observers always reverted to their full level of tonic accommodation, the associated changes in retinal image size could not account for the reported changes in perceived size.

Since accommodation changes have little effect in retinal image sizes, we can conclude that :

1. Accommodation-induced changes in retinal image size cannot have primary responsibility for any reported size changes in the perceived image.

2. Other factors may have more important effects on perceived size.

The next chapter describes experimental studies in the perception of the dimensions of objects in free space. Studies include size estimation under various experimental conditions, with monitoring of the corresponding levels of accommodation. The aim was to determine whether changes in apparent size were in any way related to errors in accommodation or whether other factors played a more important role. Major experimental factors explored were binocularity, pupil size, field of view and the difference in size perception when the subjects' refractive errors were corrected with contact and spectacle. lenses

CHAPTER 3: PERCEPTION OF OBJECTS IN FREE SPACE

3.1. Introduction

How does the human eye perceive the geometry of objects in free space? In this chapter, experiments will be described to explore several factors that affect the perception of an object's size (lateral dimension) and distance.

The experiments were divided into 2 parts: size matching experiments and experiments in which accommodation was measured.

3.1.1. Size matching experiments

The basic format of the study involved matching the apparent size of each of a series of "standard" targets with a "comparison" target of similar geometry, the standard and comparison target usually being at different distances.

The standard targets were white squares on a uniform black background. These were individually introduced on the line-of-sight of the subject, the physical dimensions of the target being adjusted so that the side lengths always subtended 2 degrees at the cornea. The cornea was chosen as a reference point in preference to the first nodal point since it can be unambiguously located in any experiment. When lit by ambient room illumination the white targets normally had a luminance of 40 cd/m^2.

The comparison target was a white square on a black background and was generated on the 270 x 200 mm screen of a visual display unit (VDU) with the aid of a computer software.. The size of the comparison target could be increased or decreased as desired by manipulating the "up" and "down" keys of the computer keyboard.

The following size matching experiments were carried out to further our understanding of size/distance perception:

1. Apparent size as a function of viewing distance.

2. Size perception under the following viewing conditions:
   i. Binocular, natural pupil and unrestricted field of view.

ii. Monocular, natural pupil and unrestricted field of view.
iii. Monocular, natural pupil and restricted field of view.
iv. Monocular, artificial pupil and partially restricted field of view.

3. The effect of instructions on size perception.

4.. After-image comparisons

5. Comparison of size perception in spectacle and contact lens corrected ametropia..

3.1.2. Measurements of accommodation

Accommodation was recorded with a Canon R-1 Autorefractor. This instrument has been widely used in accommodation studies and has been shown to have adequate validity and reliability (Matsumura et al., 1983; McBrien and Millodot, 1985). Its great advantage is that the refractive state of the eye can be recorded while targets are viewed without obstruction through a large beam splitter on the top of the instrument.

Two experiments were conducted. Their purpose was to supplement the size-matching experiments in order to find out if there was any real change in accommodation between the following pairs of conditions:

1. Natural pupil viewing and artificial pupil (1mm) viewing.
2. Binocular viewing and monocular viewing.

3.2. Size-matching experiments

As mentioned in section 3.1.1. earlier, the comparison target was generated on a VDU. The size of this comparison target could be varied and was given in arbitrary units. The maximum side length was 478 units and a single key press changed these dimensions in steps of 2 units. Calibration with a measuring ruler showed that there was a linear relationship between the dimensions of the square target and the arbitrary size units output by the computer. It was found, however, that adjustment of the luminance control of the VDU screen affected the size calibration, the size increasing with increased luminance. In all experiments, the screen luminance was therefore kept

constant at the maximal level (120 cd/m^2) and the calibration appropriate to this level of luminance was always used.

The calibration obtained when the screen luminance was maximum is shown in figure 3.1.

The correlation **y = -0.394 + 0.370x**, (where **y** is the size of the comparison target in mm and **x** is the size in arbitrary unit) was used to calculate the real size of the comparison target from the size in arbitrary units in all the size matching experiments.

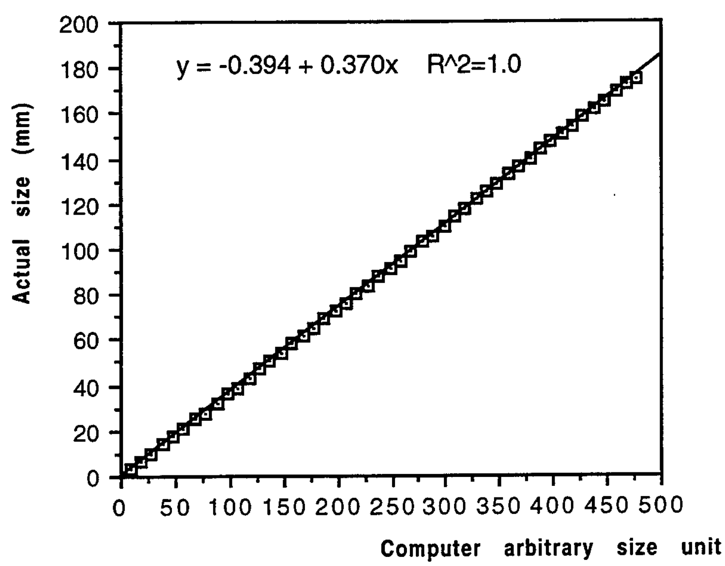


Figure 3.1: Graph showing the correlation between the computer arbitrary size unit and actual size unit (mm) when the computer screen had the maximum luminance.

3.2.1 Apparent size as a function of viewing distance

It seemed sensible to first establish the viability of the proposed matching technique and the general magnitude of any apparent size changes. A preliminary trial was therefore carried out

The trial was conducted in 2 parts. The first part used 4 subjects and only 4 viewing distances. The second part used 5 subjects with 6 viewing distances. There was a total of 7 subjects, of which 2 subjects participated in both parts of the experiment.

3.2.1.1. Subjects

Major optometric findings are given in Table 3.1 below. During the studies all subjects wore their optimal refractive correction. All achieved 6/6 or better distance vision both monocularly and binocularly. The assumption was made that any spectacle magnification effects affected the comparison and standard targets equally. (This assumption is not strictly true because we ignore the proximity factor which is a negligible factor, except for high-power lenses, Bennett and Rabbetts, 1989b, pp281-282) Any errors introduced by this assumption were less than 1% for all subjects.

Subject	**Age(sex)**	**Refractive Error**	**Amp. Accom.**	**Distance Phoria**	**Near Phoria**
LH	27(m)	RE -1.75/-1.00 x 180 LE -1.75/-0.75 x 180	9D	2 exo	6 exo
G	26(m)	RE -9.25/-0.75 x 10 LE -8.5/-1.25 x 180	11D	Ortho	13 exo
T	25(m)	Emmetropia	9D	Ortho	9 exo
S	24(m)	Emmetropia	10D	1.5 exo	0.5 exo
A	25(f)	Emmetropia	8D	1 eso	Ortho
N	25(F)	RE -1.75, LE -2.25	9D	1 eso	4 exo
AW	18(m)	Emmetropia	11D	1 eso	0.5 eso

Table 3.1: Details of subjects participated in this experiment

3.2.1.2. Procedure

The VDU comparison target was kept fixed at 2m (-0.50 D vergence) and the standard targets were viewed at distances 3 m, 1 m, 0.33 m , and 0.20 m (vergences -0.33 D, -1.00 D, -3.00 D and -5.00 D respectively) in the first trial. In the second trial, additional distances of 2 m and 0.25 m (-0.50 D and -4.00 D respectively) were included.

The comparison target was placed as close as possible to the line of sight to each of the standard targets, which were all scaled to subtend 2 degrees at the subject's cornea. Both standard and comparison targets could be seen binocularly on the same horizontal level and their adjacent edges were never more than 2 degrees apart. No restrictions were placed on viewing time and the field of view was also unrestricted, so that the general laboratory environment

provided subjects with numerous cues to the distances and relative positions of the various targets.

For each standard target, each subject adjusted the size of the comparison target until the standard and comparison appeared equal in true physical size. The instructions given to the subjects were generally as follows:

" *You are to adjust the size of the square on the VDU by pressing the UP and DOWN arrow keys. Stop and let me know when you feel that by cutting out the square on the VDU and pasting it on the standard square, it would appear to fit as exactly as possible.*"

The above instructions ensured that the subjects were matching true physical size instead of angular size. This is important because Glinsky (1989), Stylianou (1988, cited by Glinsky 1989) and Pasnak et al (1985) have hypothesised that there is an effect of different instructions on the perception of size with distance variant. The instructions should obviously tend to favour judgement being made on the basis of size constancy rather than constant visual angle. The truth of Glinsky's hypothesis will be explored further in section 3.4.

This matching procedure was repeated at least 5 times for each standard target. All readings were expressed in terms of the corresponding angular subtenses of the comparison target at the cornea. Standard targets were presented in random order.

3.2.1.3. Results

The results obtained for the angular subtense of the comparison target for each distance of the standard target are shown in Table 3.2a and Table 3.2b.

Subject	3.0m Target	1.0m Target	0.33m Target	0.20m Target
LH	2.65±0.03	1.21±0.03	1.40±0.04	1.14±0.05
G	2.43±0.04	1.36±0.01	0.61±0.02	0.38±0.04
T	2.86±0.09	1.08±0.53	0.64±0.11	0.40±0.09
S	2.68±0.08	1.18±0.02	0.35±0.02	0.21±0.02
Mean	2.66±0.17	1.21±0.12	0.75±0.45	0.53±0.41

Table 3.2a: Result obtained for the 1st part of the experiment. Means and standard deviations of the side lengths of the square comparison target at 2m (expressed in

degrees subtense at the cornea) required to match 2.00 degree subtense standard targets at the distances indicated. Binocular observation, natural pupils, no restrictions on field of view.

Subject	3m Target	1m Target	0.5m Target	0.33m Target	0.25m Target	0.2m Target
LH	2.81±0.06	1.40±0.04	1.41±0.05	1.39±0.05	1.31±0.04	1.14±0.05
N	3.15±0.07	1.58±0.08	1.12±0.05	0.90±0.04	0.66±0.04	0.57±0.02
A	2.43±0.09	1.23±0.07	0.55±0.04	0.45±0.04	0.36±0.07	0.34±0.02
AW	2.61±0.06	1.41±0.08	1.29±0.05	0.97±0.05	0.64±0.08	0.64±0.07
S	2.82±0.02	1.27±0.02	0.95±0.06	0.74±0.04	0.47±0.02	0.56±0.02
Mean	2.76±0.27	1.38±0.14	1.06±0.33	0.89±0.34	0.69±0.37	0.65±0.30

Table 3.2b: Results obtained for the 2nd part. Means and standard deviations of the side lengths of the square comparison target at 2m(expressed in degrees subtense at the cornea) required to match 2.00 degree subtense standard targets at the distances indicated. Binocular observation, natural pupils, no restrictions on field of view.

The mean results of the experiment are plotted in figure 3.2. Figure 3.2a shows the change in apparent subtense as a function of viewing distance. Also shown are the differences in angular subtense (θc - θs, where θc is the subtense of the comparison target and θs is that of the standard target) predicted on the basis of size constancy and equal angular subtense. Since the instructions for the subjects were to match true physical size, the results were also plotted in terms of percentage change of real size as a function of viewing distance. (See figure 3.2b)

Figure 3.2a

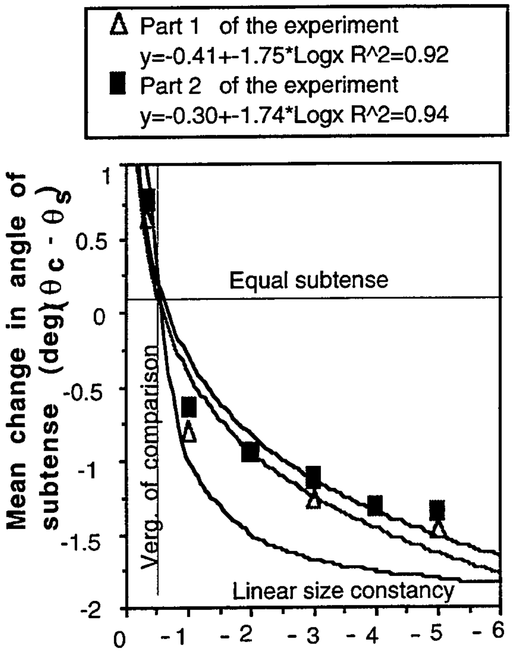


Figure 3.2b

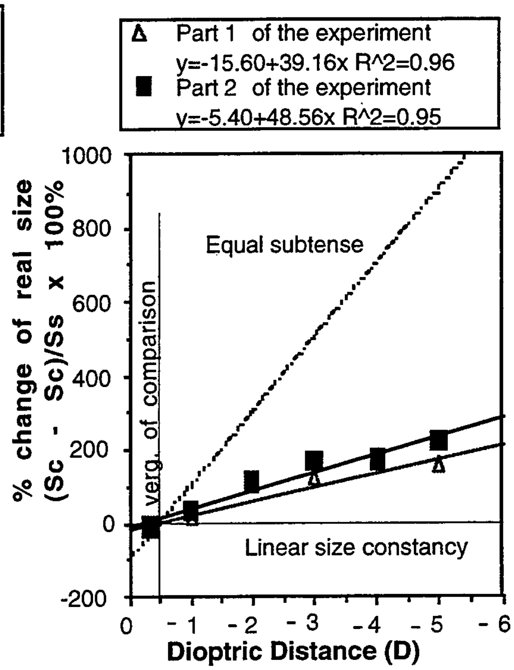


Figure 3.2a: Mean change in apparent angular size of two-degree square standard targets as a function of standard target vergence, estimated with a comparison target at 2m (dioptric distance or vergence -0.50 D). (qc is the subtense of the comparison target and qs is that (2°) of the standard target). Figure 3.2b: Apparent percentage change of real size as a function of standard target vergence, estimated with a comparison target at 2m. (Sc is the linear size of the comparison target, and Ss is that of the standard target). Binocular observation; natural pupils;no restriction on field-of-view.

There were 2 subjects (LH and S) who participated in both part 1 and 2 of the experiment. Thus it is worthwhile to plot separately the results obtained by these 2 subjects to see how consistent their size judgement were. See figure 3.3. From figure 3.3a, subject LH showed very similar size judgement for both parts of the experiment, this is especially true for the nearer standard target distances of 0.33m and 0.2m. Subject S showed less consistent responses for nearer standard target distances (0.33m and 0.20m) but consistent responses for the farther standard targets (1m and 3m). See figure 3.3b.

Figure 3.3a Figure 3.3b

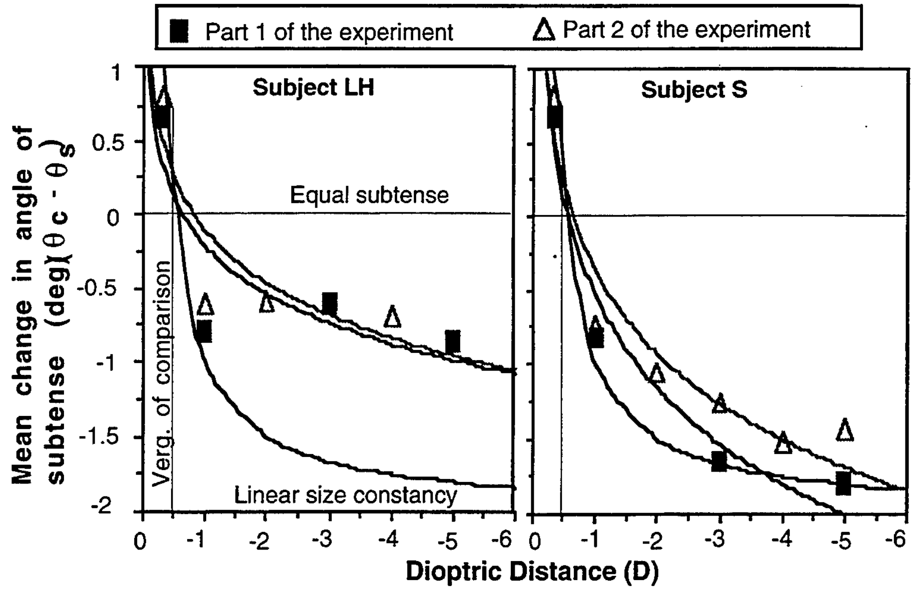


Figure 3.3: Comparing the consistency of the results obtained for subjects LH and S. Part 1 of the experiment only comprised of 4 standard target distances and part 2 comprised of 6 standard target distances. Both parts had the same experimental procedures.

3.2.1.4 <u>Discussion:</u>

The law of size constancy and the law of the visual angle were discussed in chapter 1 (section 1.2.3 and 1.2.2). If in this experiment the subjects had perceived perfect size constancy, the linear size of the comparison target (Sc mm) will be the same as the standard target (Ss mm). That means Sc = Ss, (refer to figure 1.3 in chapter 1) and the angular size of the comparison target at 2 m would be 2 x d/2 = d degree, where d metres is the distance of the standard target. Thus in perfect size constancy, the expected graph showing the perceived angular size of the comparison target over the distances of the standard targets will look like figure 3.4a.

If in this experiment, the subjects perceived the size of the matching comparison target at 2m to be 2° for all the standard targets, we could say that the subjects perceived size in such a way that the law of the visual angle was obeyed exactly. If the perceived angle of subtense of the comparison target at 2 m over the distances of the standard targets from the observer is plotted, figure 3.4b is obtained.

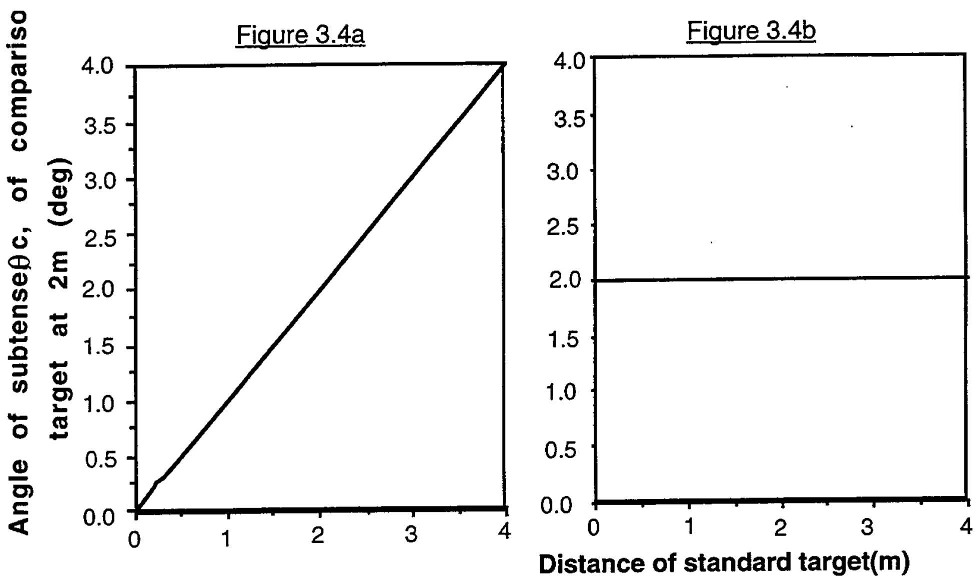


Figure 3.4a: A 45 degree diagonal line graph indicating perceived angular size obeyed the law of size constancy. Figure 3.4b: A horizontal line graph indicating perceived angular size was always 2 deg, thus obeying the law of visual angle.

Since linear plots are in some ways easier to interpret, the results obtained in part 2 of the experiment (Table 3.2b) are plotted in figure 3.5 in the similar manner to those of figure 3.4. (Part 2 of the experiment was chosen because there were two more standard target distances, 0.50m and 0.25m, and one more subject). Note that plotting the linear size of the comparison target at 2m would give plots of identical form, except that the ordinate scale would differ.

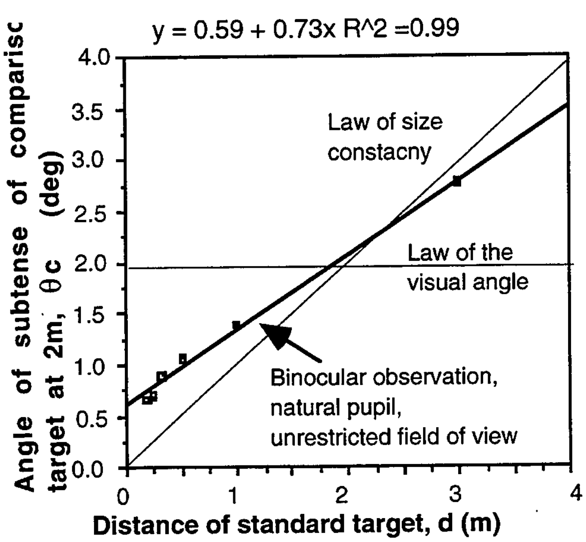


Figure 3.5: The line graph obtained falls closer to the 45 deg. line. It indicates that size perception under binocular observation, natural pupils, and unrestricted field of

view tends to follow the law of size constancy more closely than the law of the visual angle.

Remembering that the comparison target was at 2.00 metres, it was obvious from figure 3.2 and 3.5 that the standard target which was at the greater distance of 3m (vergence -0.33 D) tended to be seen larger than the standard 2 degrees subtense, and that the five near standard targets (vergence -1.00D, -2.00D, -3.00D, -4.00D and -5.00D) appeared substantially smaller than the standard 2 degrees subtense. Here we defined "larger" and "smaller" by comparing the angular perceived size with the true angular standard target size of 2 degrees. (i.e. comparison of perceived size and actual size was made with reference to the law of the visual angle.) .

The reverse was true when comparison of perceived size and actual size was made with reference to the law of size constancy (i.e. the standard target at 3 m tended to be seen smaller than its actual size, and that the five near standard targets appeared substantially bigger than their actual size).

Subsequent comparisons of perceived size and actual size of the standard targets will be made with reference to the law of the visual angle. Nominally comparisons are then made with respect to the retinal image sizes since the retinal image size was directly affected by the visual angle subtended by the target at the cornea.

As would be expected, the curve which fitted quite closely to the points in figure 3.5 passes through zero size change, corresponding to the target being seen as having its true two-degree subtense, when the vergence of the standard target is close to the -0.50 D vergence (i.e. 2 m distance) of the comparison target. Table 3.2 shows that there was, however, considerable variation between the results of the different subjects, although the data for each individual subject appeared reasonably consistent, as indicated by their low standard deviations. There is no evidence that the magnitude of the effects correlates in any way with the refractive correction of the individual subjects.

It could be argued that the results were affected by the use of the anterior pole of the cornea as a reference point rather than the first nodal point in estimating angular size with viewing distance. However, the first nodal point lies only about 7 mm behind the anterior pole of the cornea, so that even at the closest

target distance of 0.20 m this factor could only contribute less than 0.07 degrees to any apparent minification. In fact, referred to a nodal point 7 mm behind the cornea the subtenses of the targets at 3, 2, 1, 0.50, 0.33, 0.25, and 0.20 m were 1.995, 1.993, 1.986, 1.973, 1.955, 1.946 and 1.932 degrees respectively, so that this choice of reference point can only play a very minor role in the results.
In figure 3.5, the line best-fitting line through the experimental points was situated nearer to the 45° diagonal line than to the horizontal, indicating that the law of size constancy had greater influence in the subjects' size perception.

With binocular observation, natural pupil and unrestricted visual field environment, most factors which favour size constancy were present. Binocular observation provided binocular cues, and stereopsis and convergence came into play; the natural pupil ensured the accommodation loop was closed; and an unrestricted visual field provided a cue-rich environment (e.g. the monocular cues in depth perception).

Nevertheless, under this viewing condition, perfect size constancy was not found. In fact even in our normal daily size perception, we do not perceive perfect size constancy. (e.g. An object at 6 m does not look exactly the same size when it is at 3 m. We will perceive it slightly bigger at 3 m though the visual angle has doubled). Thus the law of the visual angle also played a role, though a less significant one under this normal viewing condition.

Assuming that the way we perceived size was solely governed by the law of size constancy and the law of the visual angle, and that the observed angular size of the matching comparison target was the linearly weighted sum of the sizes that would be expected on the basis of the law of visual angle and size constancy, we can express size perception mathematically in the following way:

$$\mathbf{C_V}\,\theta\mathbf{v} + \mathbf{C_c}\,\theta_\mathbf{c} = \theta\mathbf{OBS} \text{ ---------------------------------(1)}$$

and from figure 3.5, we can further deduce:

$$\mathbf{C_V}\,\theta_\mathbf{V} + \mathbf{C_c}\,\theta_\mathbf{c} = \theta\mathbf{OBS} = 0.59 + 0.73\mathbf{d} \text{---------------------(2)}$$

Where $\mathbf{C_V}$ = Visual angle weighting constant.
$\mathbf{C_c}$ = Size constancy weighting constant.

$\boldsymbol{\theta}$ **v** = Angle of subtense of comparison target if size perception obeyed the law of the visual angle. In our experiment, θ**v** was equal to 2 degrees.

$\boldsymbol{\theta_c}$ = Angle of subtense of comparison target if size perception obeyed the law of size constancy.

$\boldsymbol{\theta_{OBS}}$ = Actual subtense of matching comparison target (degree).

d = Distance of standard target from the cornea (m)

From figure 3.4a, θ**c** (deg) and **d** (m) always had the same numerical value even though their units were different. Thus we can equate θ**c** (deg) = **d** (m). Therefore, from equation (1) we can further equate:

$\mathbf{C_v}\,\theta_\mathbf{v} + \mathbf{C_c}\,\mathbf{d} = 0.59 + 0.73\,\mathbf{d}$ -------------------------- (3)

In our experiment, the angular size of our standard target was always 2 degrees thus size perception would always be 2 degrees under the law of the visual angle. Therefore $\theta = 2$ degrees, and equation (3) can be further summarised to:

$2\mathbf{C_v} + \mathbf{C_c}\,\mathbf{d} = 0.59 + 0.73\mathbf{d}$ ----------------------------(4)

When **d** was very small, say **d** = 0, 2 **Cv** = 0.59. Therefore,
Cv = 0.59/2 = 0.295 ≈ 0.30

Equating the coefficients of the variable **d**
$\mathbf{C_c}$ = 0.73

Thus, under these conditions, size constancy was weighted much more heavily than constant visual angle.

We can verify the equation, $\mathbf{C_v}\,\theta_\mathbf{v} + \mathbf{C_c}\,\theta_\mathbf{c} = \theta_\mathbf{OBS}$, with the results we obtained in this experiment. At **d** = 3m, the perceived size is 2.76 degrees. Thus $\theta_\mathbf{OBS}$ = 2.76 degrees. Substituting the values of $\mathbf{C_c}$ and $\mathbf{C_v}$, we get:

> 0.30x 2 degrees + 0.73 x 3 degrees = 2.76 degrees
> 0.60.degrees + 2.19 degrees = 2.72 degrees
> 2.79 degrees ≈ 2.76 degrees

It was noted that $(\mathbf{C_v}\,\theta_\mathbf{v} + \mathbf{C_c}\,\theta_\mathbf{c})$ was not always equal to $\theta_\mathbf{OBS}$. The reason was that the $\theta_\mathbf{OBS}$ points we obtained for the 6 distances in the experiment did

not fit exactly to the curve in figure 3.5. If the **qOBS** point lay higher than the line graph (as at 0.50 m distance) $(C_V\,\theta + C_c\,\theta_c)$ would be smaller than θ_{OBS}. Nevertheless by knowing the constant values of C_V and C_c we can predict the approximate values of observed size at any distances under this viewing condition. Moreover if $C_c > C_V$, (as in this viewing condition) it indicated that the law of size constancy played a more important role in size perception than the law of the visual angle and vice versa.

In subsequent experiments, the value of the constants C_V and C_c were found to change when the viewing condition changed, so that the values of C_V and C_c usefully summarise the relative contribution of size constancy and visual angle under the prevailing viewing conditions.

3.2.1.5 Conclusion

With binocular observation, natural pupils and an unrestricted field of view, there was a fairly substantial minification effect in perceived size especially at the nearer distances. (i.e. angular perceived size was smaller than angular size subtended by the standard target) With farther distance (i.e. greater than 2 m) there was a magnification of perceived size.(i.e. angular perceived size was bigger than angular size subtended by the standard target.)

If we assumed that the way the subjects perceived size was governed by the law of size constancy and the law of the visual angle, we can express size perception mathematically in equation (1). Under this viewing environment, size perception tended to follow the law of size constancy more closely than the law of the visual angle.

Next efforts were made to isolate the factors that contributed to the magnitude of the minification effect.

3.2.2 To determine the effect of size perception under 4 different viewing conditions

In this experiment, size perception was measured as a function of several viewing distances under 4 viewing conditions. The same size matching technique, as in section 3.2.1.2, was used in the following 4 viewing conditions.

3.2.2.1 Binocular, natural pupil and unrestricted field of view

This viewing condition was actually the same viewing condition as section 3.2.1. Thus the results obtained in that section will be used here.

3.2.2.2 Monocular, natural pupil and unrestricted field of view

The procedure for this experiment was similar to section 3.2.1 except that the subjects occluded one eye during size matching.

3.2.2.3 Monocular, natural pupil and restricted field of view

In this viewing condition, we tried to determine the effect of removing all peripheral and paracentral distance cues on size perception. Tunnel vision was created by placing a frame with a small central rectangular hole in front of the viewing eye. The frame was made of a 59 cm by 84 cm black cardboard mounted on a wooden frame. The central rectangular hole had a dimension of 2.2 cm by 1 cm. If the frame was placed at a distance of about 120 mm from the eye, the field of view was limited to about 5 by 11 degrees.

The procedure was similar to section 3.2.1 except that the frame was mounted in front of the observing eye (dominant eye) and its distance from the eye was adjusted until the subjects could only see the comparison and standard targets. (Even the borders of the VDU could not be seen).

3.2.2.4 Monocular, artificial pupil and partial restriction of field of view

In all the previous experiments, it was necessary for the subjects to change their accommodation during the matching task, since the two targets under comparison were at differing distances. If, however, a small artificial pupil is placed before the eyes, the depth of focus increases substantially and, as a result only minor changes in accommodation are elicited by objects at varying distances. (Ripps et al., 1962; Hennessy et al. 1976; Ward and Charman, 1987) Thus errors of accommodation are larger with a small pupil and hence, if errors in accommodation are responsible for the changes in apparent size, one would expect the size changes to be larger than for a larger, natural pupil.

Any small artificial pupil also restricts the field of view. The artificial pupil was a 35 mm diameter disk of opaque material with a 1 mm hole in the centre. It was placed in a trial frame and lay in the spectacle plane at a vertex distance of about 12 mm. Thus it allowed a less than 5 degrees central field to be seen and restricted the inner edge of the peripheral field of view to 55 degrees upward, nasal war, downward and temporal ward. We know that the visual field for a normal eye is about 50 degrees upward, 60 degrees nasal-ward, 70 degrees downward and 90 degrees temporal-ward. Thus by placing the artificial pupil in front of the eye, there was a small loss of about 5 degrees extreme nasal field, 15 degrees of extreme downward field and 35 degrees of extreme temporal field

During the matching task, additional lighting was employed to maintain the retinal illuminance for the standard targets at an approximately constant level. The procedure for this experiment was similar to section 3.2.1 except that size matching was done with a 1 mm artificial pupil on 1 eye while the other eye was occluded.

3.2.2.5 Subjects

Refer to Table 3.3 for those subjects which participated in this experiment. Their optometric data is given in Table 3.1.

Viewing Conditions			
Natural	**Monocular**	**Restricted Field**	**Artificial Pupil**
LH	LH	LH	LH
G	G	N	G
T	AD	AD	AD
S	S	AW	S
N	N	S	N
AD	AW		
AW			

Table 3.3: Table showing the subjects participating in the experiment. ***Natural*** *- Binocular, natural pupil and unrestricted field of view.* ***Monocular*** *- Monocular, natural pupil and unrestricted field of view.* ***Restricted Field*** *- Monocular, natural pupil and restricted field of view.* ***Artificial Pupil*** *- Monocular, artificial pupil and partially restricted field of view.*

3.2.2.6 Results

Appendix 3.1 gives mean perceived angular size of the comparison target at 2 m as a function of the distance of the 2 degree subtense standard target for each subject. Figures 3.6 and 3.7 summarise the results.

Figure 3.6 indicates the composite mean of perceived angular size of the comparison as a function of the distance of the standard target.

Figure 3.7 indicates the composite mean change in perceived angular size (perceived angular size - 2 deg) as a function of the dioptric distance (vergence) of the standard target.

It was noted from figures 3.6 and 3.7 that all the line graphs for each viewing conditions meet at about 2m or -0.5 dioptric distance, which was the location of the comparison. target.

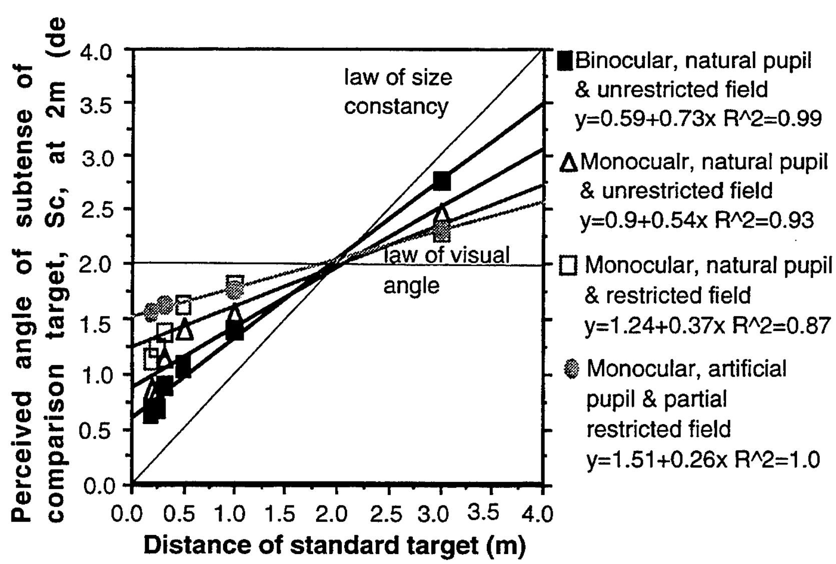


Figure 3.6: The apparent size as a function of the distance of standard target under 4 different viewing conditions.

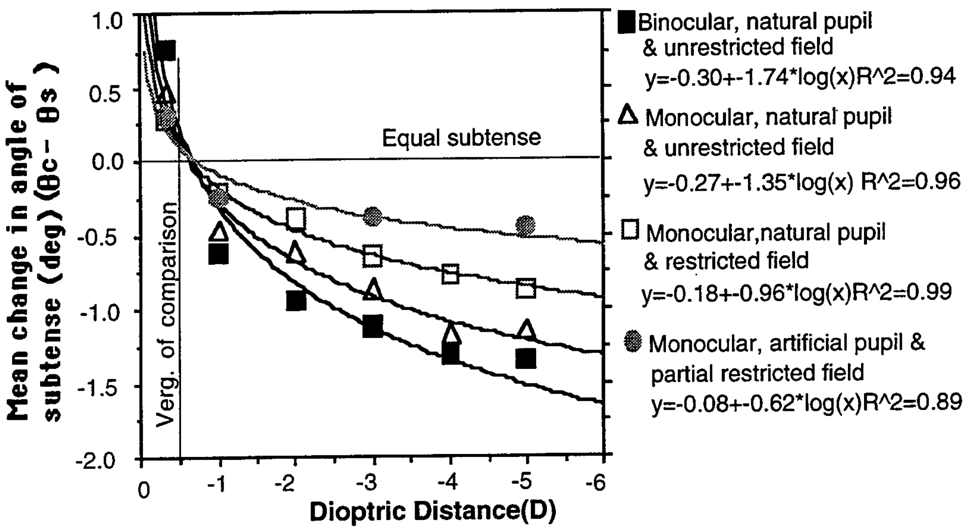


Figure 3.7: Mean change in apparent size of two-degrees square standard targets as a function of target vergence, estimated with a comparison target at 2m. Comparing the four viewing conditions.

Table 3.4 shows the visual angle weighting constant (**C_V**) and the size constancy weighting constant (**C_C**) in each of the 4 viewing conditions.

Constant	VIEWING CONDITIONS			
	Binocular Natural Pupil Unrestricted Field	Monocular Natural Pupil Unrestricted Field	Monocular Natural Pupil Restricted Field	Monocular Artificial Pupil Partial Field Restriction
C_V	0.30	0.45	0.62	0.76
C_C	0.73	0.54	0.37	0.26

*Table 3.4: Comparing the **Cv** and **Cc** constants of the 4 various viewing conditions. **Cv** is the Law of Visual Angle constant and **Cc** is the Law of Size Constancy constant. If **Cc** > **Cv** the Law of Size Constancy has a greater influence on size perception and vice versa. It is noted that **Cv** + **Cc** is approximately equal to 1.*

3.2.2.7 Discussion

The following points were noted:

1. Under monocular, natural pupil and unrestricted field condition, size perception tends to move closer towards the law of visual angle than it does under binocular observation. The $\mathbf{C_V}$ constant was 0.48 and $\mathbf{C_C}$ constant was 0.52, and $\mathbf{C_C}$ was still greater than $\mathbf{C_V}$. Thus the law of size constancy still played a more important role than the law of the visual angle in this viewing condition.

In this monocular viewing condition, the effects of convergence were absent. Convergence is known to contribute to the micropsia found with near objects (e.g. Duane, 1900; Heinemann et al., 1959; Alexander, 1975; Hollins, 1976). Roscoe (1984) hypothesised that occluding one eye would cause it to regress towards its resting focus. If this were true, as accommodation in each eye is not independent, the other seeing eye would also tend to move towards the resting-accommodation position and the actual state of accommodation would be a compromise between the stimulus distance and resting-accommodation distance. Thus this compromise accommodation could cause accommodative micropsia. As mentioned in section 1.2.4.1.5 in this thesis, we were very dubious about Roscoe's above hypothesis and experiments to test this hypothesis are described later in this thesis. (section 3.3.2)

In addition, stereopsis was absent in monocular viewing and thus the binocular cues in depth perception were absent.

2. By restricting visual field to view only the comparison target and standard target (i.e. less than 10 degree of visual field), we further shift size perception towards the law of the visual angle and away from size constancy.

The $\mathbf{C_V}$ and $\mathbf{C_C}$ constants in this viewing condition were 0.62 and 0.37 respectively. Since $\mathbf{C_V} > \mathbf{C_C}$, in this viewing condition the law of the visual angle plays a more important role than the law of size constancy in size perception. Note, however, that the regression line fit was less convincing under the more restricted conditions, particularly for the shorter distances of the standard target.

This result emphasises that peripheral vision also plays a role in size perception. Removal of peripheral cues to distance shifts size perception away from the law of size constancy.

3. In the viewing condition with the 1 mm artificial pupil, although there were inter-subject differences (refer to Appendix 3.1), all individuals followed the same general trend of showing smaller changes in apparent size with the artificial pupil. All the results with the artificial pupil were closer to the "ideal" value of 2-degrees. (i.e. they tended to obey the law of the visual angle more).

The composite mean apparent size under the artificial pupil condition was plotted as a function of standard target distance and compared with the apparent size under the other 3 viewing condition. This was not an exact comparison because unlike the other 3 viewing condition only 4 standard target distances were observed. Nevertheless, it did give us a general indication of the effect of an artificial pupil on size perception when comparing with binocular observation, monocular observation and with restricted field-of-view.

From figure 3.6, the line graph for the apparent size with the artificial pupil is very close to the line graph with the restricted visual field. It was not surprising because the artificial pupil did in fact restrict part of the field of view, although it also affected the accommodation exercised.

The $\mathbf{C_V}$ and $\mathbf{C_C}$ weighting constants under this viewing condition were 0.76 and 0.26 respectively. Since $\mathbf{C_V}$ was almost 3 times higher than $\mathbf{C_C}$, the law of the visual angle had a 3 fold greater influence on size perception than the law of size constancy .

3.2.2.8 Conclusion

An absence of binocular cues, stereopsis and absence of peripheral cues to distances tend to shift size perception towards the law of the visual angle. In other words, size constancy tends to break down, even though the subjects are still trying to match the physical size of the standard and comparison targets.

It was tempting to ascribe the differences in size perception with and without artificial pupil viewing conditions to differences in accommodation, although it

was also possible that the somewhat different restrictions in the field of view associated with the artificial pupil might also play an important role.

The rest of this chapter will be concerned with more detailed exploration of some of the factors that might influence these size judgements. (i.e. instruction set, type of refractive correction worn, and accommodation under small pupil, monocular or binocular viewing conditions).

3.2.3 Effect of instructions on size perception

Gilinsky (1989) hypothesised that size perception could be affected by 3 main types of instructions given to the subject before he/she performed the matching task. The 3 types of instructions were objective instructions or "true size" instructions, "picture-image" instructions, and "visual angle" instructions.

In his airport experiment, Gilinsky (1955), compared the effect of different instructions on size matches made to objects of unknown size (white isosceles triangles, 42 to 78 inch tall), placed one at a time along a runway at various distances from 100 to 4000 ft, outdoors, on clear days affording many cues to distance. The comparison triangle, 100 ft away and 36° to the right of the subject, could be varied in height from 0 to 86 inch. Subjects served under 2 different conditions of instruction that demanded contrasting sets: a set for matching objective, "true size" and a set for matching "picture-image" size. The result of the experiment is summarised in figure 3.8.

"True size" instructions gave matches in size that increased with distances, and were closer to the theoretical curve for size constancy matches. In contrast, the results for the "picture-image" instructions were closer to the theoretical curve for visual angle matches. However Gilinsky said that these "picture-image" matches were not estimated angular size matches but genuine matches of immediate perceived size.

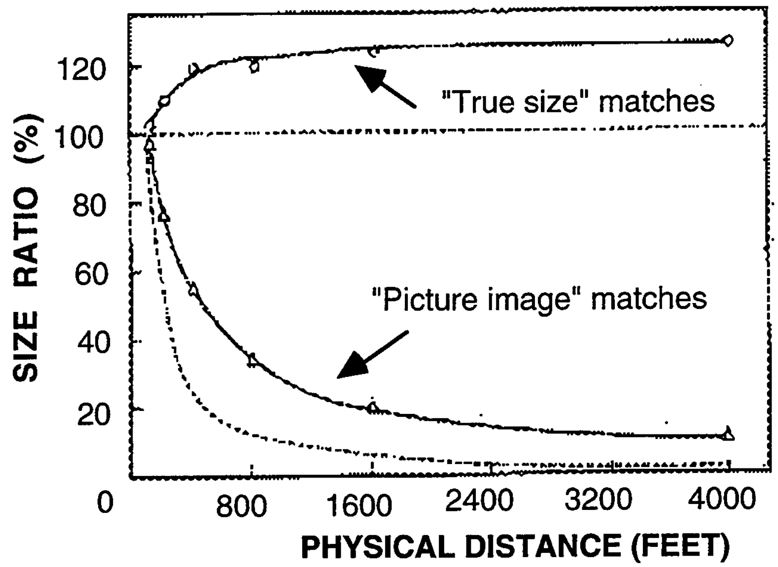


Figure 3.8: "True size" matches (circles) and "Picture-image" matches (triangles) plotted as ratios of the size of the variable triangle to the size of the standard triangle to which comparison was made at various distances from 100 to 4000 ft. The horizontal dashed line represents the theoretical function of size constancy; the lower dashed curve represents the actual size of the retinal image or visual angle. Data from Gilinsky (1955)

In another experiment, (Stylianou, 1988, cited by Gilinsky 1989), Stylianou used an additional instruction, the "visual angle" instructions, which based on estimates of visual angle. These three sets of instructions were randomised and counterbalanced across 3 standard disks (6, 12 and 24 inch in diameter) and across subjects. Subjects held a tape measure on their lap and looked down from the suspended disk to mark its perceived or estimated width as demanded by the particular instruction. Each subject served individually under all 3 conditions of instruction, 3 conditions of object distance and 3 different size disks, shown one at a time. Figure 3.9 showed the result. The "picture-image" instructions consistently produced size matches intermediate between those of the other two instructional sets.

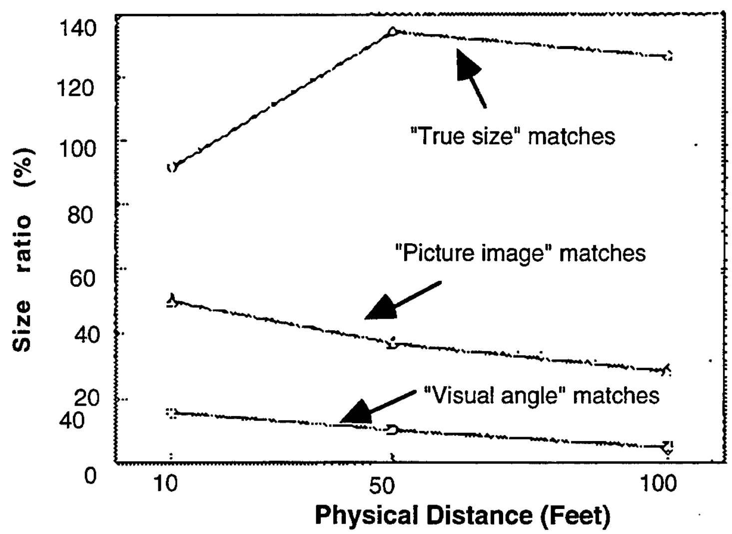


Figure 3.9: Mean size matches plotted as ratios of the mean standard size object as a function of distance for three sets of instructions: "True size", "Picture-image" and "Visual angle" matches. Data from Stylianou (1988)

In our earlier experiments (section 3.2), the instruction set was effectively designed to produce a "true size" match, although at distances much shorter than these used by Gilinsky and Stylianou. In the present experiment, we aimed to explore the effect of these 3 instructions on size perception at the much nearer distances of 0.25 m and 3 m.

3.2.3.1. Procedure

The same size matching methods and targets described in section 3.1.1 were used in this experiment. The variable comparison square target was fixed at 2 m from the eyes of the subject. The standard squares were a white on a black cardboard background, and each subtended 2 degrees at the eyes of the subject. There were 2 standard squares; one situated at 0.25 m and the other at 3 m from the subject. They were presented one at a time. The angular separation (about 1 to 2 degree) between the comparison and standard targets was kept at a minimum to reduce eye movement during size judgement.

3 types of instructions, "true size", "picture-image", and "visual angle" instructions, were given to the subjects in a random order. The instructions were simply known as instructions A, B and C to the subjects. All instructions were clearly written down and each subject was given as much time as he/she

needed to understand it. Subjects were free to ask for further clarification about the instructions if they were at all doubtful about the task..

The 3 instructions were as follows:

1. <u>Instruction A: "True size" instruction</u>

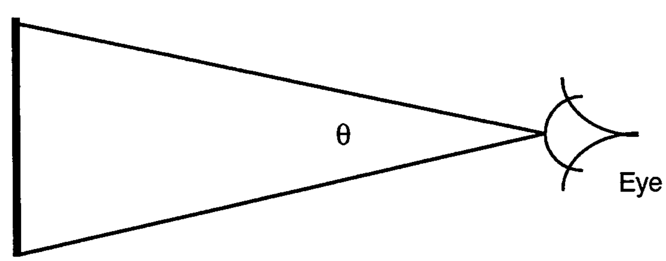
"Suppose we were to place the ***variable square*** (i.e. on the VDU) beside the ***standard square***; how big would you have to make the variable square so that it would be exactly the **same size** as the standard? Now so adjust the variable square until it is equal to the standard in size. **(i.e. if you measured both with a ruler, they would measure exactly the same size.)** "

2. <u>Instruction B: "Picture image" instruction</u>

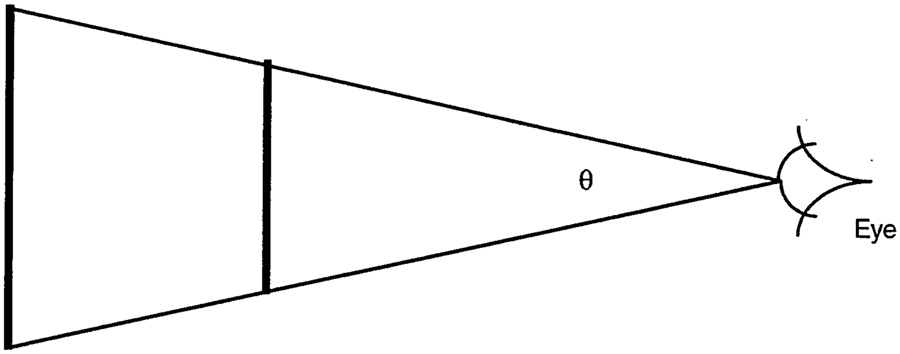
"Imagine that the field of view is a scene in a picture or photograph. Every image in the picture is fixed in size. If you were to cut out the image of the ***variable square***, and paste it on the fixed image of the ***standard square*** would the 2 images be just the same size? Now adjust the size of the ***variable square*** until the **cut-out image** of the ***variable square*** would be exactly equal to the fixed image of the ***standard square*** in size. **(i.e. that the two images would actually coincide.)**"

3. <u>Instruction C: "Visual angle" instruction</u>

"The ***standard square*** which is at this distance presents a visual angle, say q, at your eye. (see diagram below.)



If we want to maintain the same visual angle, q, at a farther or nearer distance, the size of the square must also be increased or decreased respectively. (see diagram below).



Now adjust the ***variable square*** on the VDU until you feel that it subtends the **same visual angle,** θ, at your eye as the ***standard square.*** **(i.e. that if you measured both with a protractor, they would measure exactly the same angle from your eye)** "

The subject was seated comfortably, and an instruction (selected at random) was presented to him/her. The subject read the instruction and, after it had been ensured that he/she understood the instruction, the experiment. was begun A single standard square (subtended 2 degrees at the subject's eyes) was presented at either 0.25 m or 3 m (at random) from the subject, and it was ensured that both the variable square and the standard square were viewed binocularly. Each subject was required to look at the standard square (situated at 0.25 m or 3 m) and based on his/her understanding of the instructions given, he/she was required to adjust the size of the variable square. The subject was given as much time as possible to make the size judgement by adjusting the size of the variable square. The subject was not restricted to using any particular method in judging the size of the standard square, as long as the head remained fixed on the chin rest. The room lights were all switched on and no attempt was made to reduce any distance/size cues which might be available. 10 readings were obtained for each standard square distance. Then the experiment was repeated for the other standard square distance, using the same instruction.

After the subject had completed each instruction, he/she was asked to come back again on another day for another instruction, until he/she had completed the 3 instructions.

No 2 instructions were presented to the subject in a single day. This was to minimise the possibility of the subjects using the same method in judging the size of the squares for any 2 of the instructions. Another reason was to prevent our subjects from getting tired and losing interest in what they were doing.

3.2.3.2 Subjects

A total of 7 subjects participated in this experiment. All had corrected vision of at least 6/6 in both eyes. Ages ranged from 19 years to 26 years. 6 of them were male and 1 female. All subjects were UMIST university students, thus it was assumed that they were intelligent enough to understand the instructions.

3.2.3.3 Results

When the standard square was at 0.25 m, the perceived angular size of the variable square which was situated at 2 m was as shown in figure 3.10 for the 3 types of instruction.

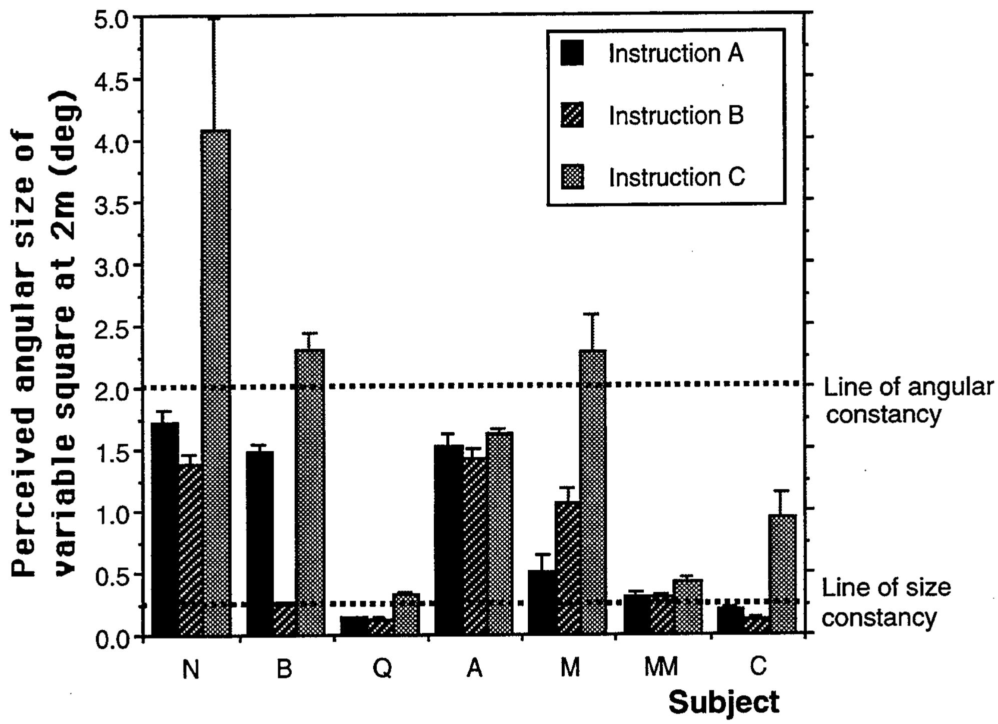


Figure 3.10: Effect of instructions on size judgement of a fixed square which subtended 2 degree and situated 0.25 m from the eye. The variable square was situated at 2 m. Instruction A: "True size" instructions; Instruction B: "Picture image" instructions; Instruction C: "Visual angle" instructions.

From the graph, the following observations were made:

1. Instruction C ("Visual angle" instructions) always produced the largest perceived angular size for all the 7 subjects.

2. Except for subject N, all perceived angular size for instruction C lay closer to the line of angular constancy than the perceived size for instructions A and B. (The line of angular constancy indicated that perceived size was directly influenced by the angle subtended by the retinal image or was equivalent to the visual angle of the standard square, which was 2 degrees in our experiment)

3. Except for subject M, "picture image" instructions (i.e. instruction B) produced the smallest angular perceived size when compared to instruction C and A. Similarly, except for subject M, "true size" instructions (i.e. instruction A) consistently produced angular perceived size which was intermediate between instruction C and B. This was in contrast with Stylianou's (1988) result (refer to figure 3.8) which showed that the "picture image" instructions consistently produced size matches intermediate between "true size" and "visual angle" instructions.

4. Using the 2 tails, paired t-test, all instructions showed a significant difference among the 3 instructions except for subject MM between instruction A and B.

5. In 3 subjects (Q, M and C) under “true size” instructions, and in 2 subjects (B and A) under “picture image” instructions, the perceived angular size lay closer to the line of size constancy than instruction C. (The line of size constancy indicated that perceived size was equal to the size of the fixed standard square. In this case, the size of the 0.25 m standard square was 8.72 mm, and at 2 m 8.72 mm subtended 0.25 degrees to the eyes) Subject MM had exactly the same perceived angular size under “true size” and “picture image” instructions, which also lay close to the line of size constancy.

Figure 3.11 shows the composite mean of perceived angular size for all the subjects for the 3 different instructions.

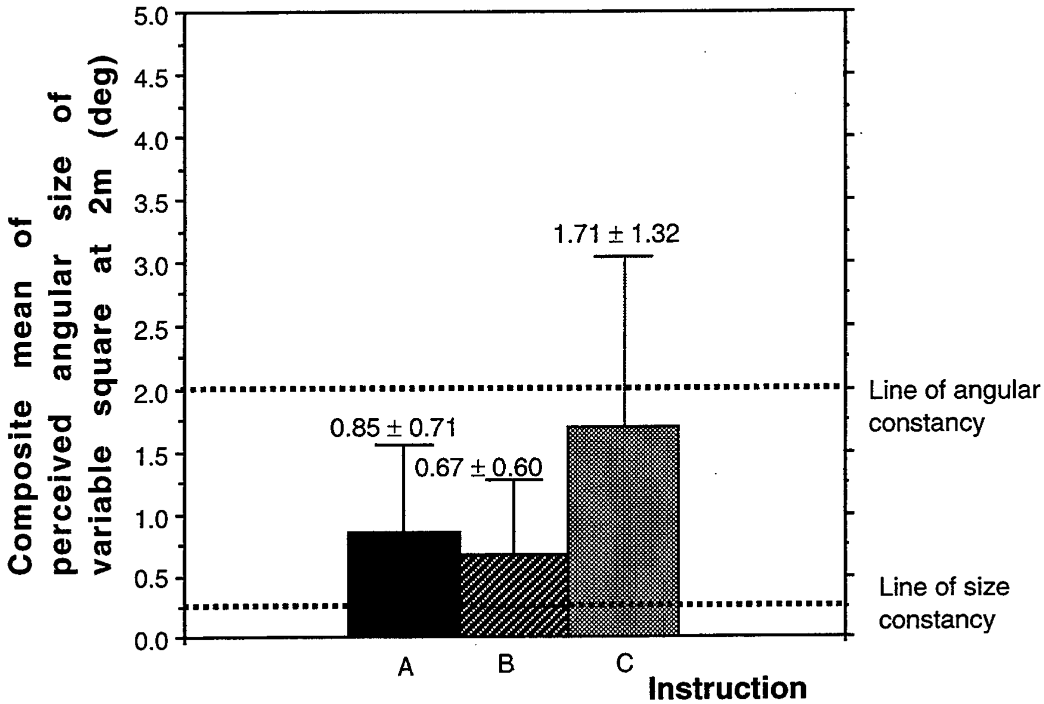


Figure 3.11: Composite mean of the perceived angular size of the variable square for all the subjects for the 3 different instructions. To show the effect of instructions on size judgement of a fixed square which subtended degree and situated 0.25 m from the eye. Instruction A, B and C were "True size", "picture image" and "visual angle" instructions respectively.

When the standard square was at 3 m, the perceived angular sizes of the variable square which was situated at 2 m are shown in figure 3.12 for the 3 types of instructions.

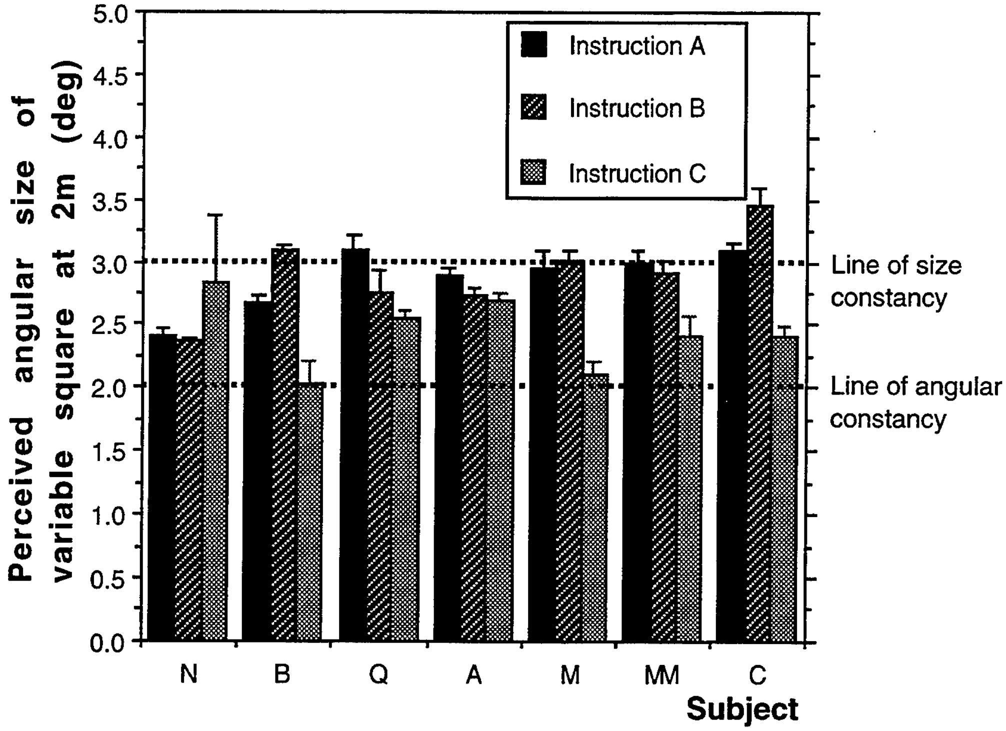


Figure 3.12: Effect of instructions on size judgement of a fixed square which subtended 2 degrees and was situated 3 m from the eye. The variable square was situated at 2 m. Instruction A: "True size" instructions; Instruction B: "Picture image" instructions; Instruction C: "Visual angle" instructions.

From the graph, the following observations were made:

1. Except for subject N, "Visual angle" instructions produced the smallest angular perceived size and the results also lay closer to the line of angular constancy than the other 2 instructions.

2. In 4 subjects (Q, A, MM and C), "true size" instructions produced perceived angular size which lay closer to the line of size constancy. In 2 subjects (B and M), "picture image" instructions produced perceived angular size which lay closer to the line of size constancy.

3. Using the 2 tails, paired t-test, 3 subjects (N, M and MM) shown no significant difference between the perceived angular size for "true size" instructions and "picture image" instructions. For subject A there was no significant difference in perceived angular size between "picture image" instructions and "visual angle" instructions.

Figure 3.13 showed the composite mean of perceived angular size of all the subjects for the 3 different instructions.

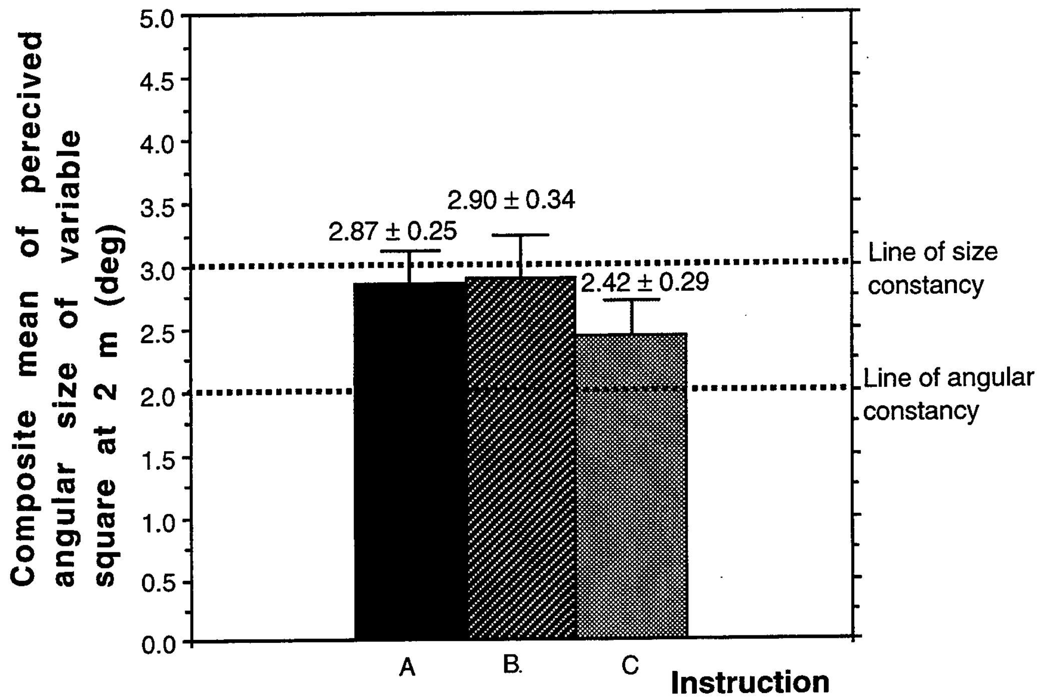


Figure 3.13: Composite mean of the perceived angular size of the variable square of all the subjects under the 3 different instructions. To show the effect of instructions on size judgement of a fixed square which subtended degree and situated 3 m from the eye. Instruction A, B and C were "True size", "picture image" and "visual angle" instructions respectively.

In comparison with the results when the standard target was at 0.25m, the 3 m target produces much smaller errors in size estimation. Nevertheless instructions A and B produce results which are closer to size constancy.

3.2.3.4. Conclusion

In a cue-rich, binocular viewing conditions, size perception tended to follow the law of size constancy. In a restricted field and monocular viewing conditions, size perception tended to follow the law of visual angle. (Holway and Boring, 1941). In our experiment, the viewing condition favoured size constancy thus it was not surprising to note that "true size" and "picture image" instructions lay closer to the line of size constancy for both standard target distances.

Our results were not convincing enough to indicate the difference in "true size" instructions and "picture image" instructions in size judgement. Generally, we could conclude that under these both instructions and in a cue-rich viewing conditions, most subjects tended to judge size according to the law of size constancy. Perhaps it was the cue-rich viewing conditions which produced size constancy perception and the instructions may have little effect.

On the other hand, the "visual angle" instructions tended to shift perceived angular size towards angular constancy and away from size constancy at both near and far standard target viewing distances even in a cue-rich viewing conditions.

Thus in future size matching experiments, if we really want to reflect the true perceived size in a particular viewing conditions, we have to choose the right instructions. A "visual angle" instruction will bias size perception towards angular constancy even though the viewing conditions favour size constancy.

3.2.4. After-image comparisons

Although accommodation-dependent changes in the size of the optical image on the retina were unlikely to be responsible for changes in apparent size it was felt to be desirable to carry out a further exploratory experiment using after-images to see if significant size changes could be detected.

3.2.4.1. Procedure

A photographic flash unit was masked to leave two clear, vertical bar apertures, with inner edges separated by 2 degrees at the viewing distance used (28.6 cm). The subject fixated monocularly a point midway between the bars and the flash was fired. The subject's task was then to compare the dimensions of the resultant after-image with those of each of the standard two-degree targets, viewed at their appropriate distances (3 m, 1 m, 0.33 m and 0.20 m) (See figure 3.14). It would be expected that if retinal image size was invariant with target distance the after-image would always appear to match the dimensions of the targets. (Emmert's Law, see section 1.2.1). On the other hand, marked changes with distance in the sizes of the retinal images of the standard targets would mean that the after-image would only match the standard when both were observed at the same distance.

Matching after-images in this way is difficult and requires some experience, since changes in fixation only affect external targets, not the projected after-image and the after-image periodically fades. (The after-image could be reinforced by a second flash)

In an initial qualitative experiment, 2 subjects (LH and O) simply had to judge whether the after-image separation was smaller, larger or equal to the width of the standard target.

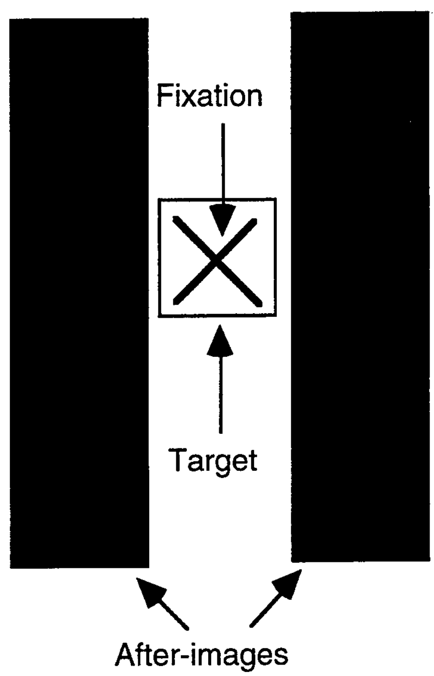


Figure 3.14: Appearance of standard target and after-image if the retinal image of the standard target is reduced in size due to accommodation.

In the quantitative part of the experiment, an attempt was made to estimate the accuracy or error of the size estimate made by the subjects in comparing the separation of the after-image with a nominally 2 degrees of the standard target.

The subject's task was to adjust the distance (by means of a simple pulley system) between the standard target and the eye until they felt that the dimensions of the resultant after-image were similar in size, just bigger in size and just smaller in size than the standard target. Throughout the procedure, the subject was instructed to fixate on the standard target. With the actual linear size of the standard target and its distance from the eye (as selected by the

subject) known, the angle of subtense of the standard target could be calculated. Five subjects participated in this trial. (Subjects LH, N, T, S and AD)

3.2.4.2. Result

The qualitative matching results reported for each two degree standard target at 4 different distances are summarised in Table 3.5.

For subject LH, the after-image separation was smaller than the subtense of the farther standard targets (i.e. 3 m and 1 m). Subject O reported the reverse, i.e. the after image was larger.

For the nearer standard targets (0.33 m and 0.20 m) both subjects reported that the after-image separation was similar in size to the targets. Substantial accommodation must be exerted in order to see the nearer standard targets and this did not apparently affect the perceived size of the targets in relation to the after-image.

	2 degree Standard Target's Distance			
Subject	3 m	1 m	0.33 m	0.20 m
LH	Resultant afterimage separation was SLIGHTLY SMALLER than standard target	Resultant afterimage separation was SLIGHTLY SMALLER than standard target	Resultant afterimage separation was SIMILAR to standard target	Resultant afterimage separation was SIMILAR to standard target
O	Resultant afterimage separation was SLIGHTLY BIGGER than standard target	Resultant afterimage separation was SLIGHTLY BIGGER than standard target	Resultant afterimage separation was SIMILAR to standard target	Resultant afterimage separation was SIMILAR to standard target

Table 3.5: Qualitative matching of 2 degree resultant after-image to the 2 degree standard targets at their appropriate distances.

The results for the quantitative study are summarised in Table 3.6.

Subject	Mean angle of subtense when after-image separation was JUST SMALLER than standard target (deg)	Mean angle of subtense when after-image separation was SIMILAR to the standard target(deg)	Mean angle of subtense when after-image separation was JUST BIGGER than standard target(deg)
LH	2.10	1.99	1.76
N	2.28	2.14	2.13
T	2.21	1.98	1.98
S	2.05	1.91	1.79
AD	2.04	1.82	1.76
Mean	2.14±0.11	1.97±0.12	1.88±0.17
Error	7.00%	-1.50%	-6.00%

Table 3.6: 3 forms of matching of a nominally two-degree after-image to a 2 degrees standard target. (i) When subject felt that the after-image was just smaller than the standard target; (ii) when the subject felt that the after-image was same size as the standard target; and (iii) when the subject felt that the after-image was just larger than the standard target. The error was obtained by the formulae: [composite mean - 2 degrees]/2 x 100%

The results suggest that the errors made by subjects in this after-image comparison were fairly small. The subjects mean perceived angular size of the standard needed to be 1.97 deg in order for them to perceive it to be equal to the separation of the after-images, which was 2 deg. Thus the mean error was only 1.5%.

The perceived mean angle of subtense of the standard target needed to be 2.14 deg in order for the subjects to notice that the standard target was bigger than the separation of the after-images. We knew that the separation of the after-images was 2 deg, thus a 7% increase in perceived size of the standard target was required in order to detect that the standard target was just bigger.

Similarly, a 6% decrease in perceived size of the standard target was required for the subjects to detect that the standard target was just smaller than the separation of the after-images. These changes are compatible with the standard deviations in the mean results.

3.2.4.3. Discussion

These results set a firm limit to retinal image size changes caused by accommodation of up to 5D. It is worth commenting that this after-image technique also set constraints on the extent to which retinal stretch caused by accommodation may affect perceived image size. There is evidence (Moses, 1987; Blank and Enoch, 1973; Enoch, 1973, 1975; Hollins, 1974; Miles, 1975) that tractional forces exerted on the retina and choroid by the ciliary body during accommodation may "stretch" the retina so that its anterior margin moves forward with respect to the globe. The effect of such stretch would obviously be to reduce the number of receptors covered by an optical image of constant area, which presumably would result in a smaller perceived image at higher levels of accommodation. With the after-image method, the after-image would expand with the stretched retina, so that the nearer standard targets should appear smaller (assuming that all target images had constant size, irrespective of the target distance). The apparent absence of such an effect therefore set an observational upper limit of about 10% on the extent of the stretch. In fact, with the current level of development of the after-image method, this upper limit was much greater than the increase of about 1% inferred to occur by Enoch (1973), although it was closer to the stretch of 4% that Hollins (1975) suggested might occur in the central retina for accommodation of about 10D.

3.2.4.4. Conclusion

In the qualitative part of the experiment, there was no evidence to show that there was large accommodation-dependent changes in the size of the optical images on the retina when our 2 subjects viewed the nearer standard targets. The quantitative part of the experiment showed that size matches of after-images with real targets were fairly accurate (only 1.5% of error) and any mis-matches of 10% or more should be easily detectable.

Thus the much larger amount of micropsia perceived for the nearer targets in the experiments described in section 3.2.1 and 3.2.2 is unlikely to be due to

accommodation-dependent changes in the size of the optical images on the retina.

3.2.5. Comparing size perception in spectacle and contact lens corrected ametropia

In natural vision, the object space is the same for each eye, apart from a slight difference in viewpoints. (refer to section 5.1) Wearing spectacles creates an entirely different situation. A common object space is now replaced by 2 separate image fields formed by the right and left spectacle lenses. As a result, spectacle lenses may affect the following:

1. The size and possibly the shape of the retinal images.
2. The amount of accommodation needed in near vision.
3. The ocular rotations needed to place the retinal image of a given point in space on the fovea of each eye.
4. The relationship between accommodation and convergence.

In general, these side-effects are caused by the lens-eye separation (back vertex distance) and the fact that the lens does not move with the eye. Consequently, they are either absent or are much less pronounced when contact lenses are worn. (Bennet and Rabbetts, 1989b). Although simple spectacle magnification effects would be expected to affect both standard and comparison targets equally, accommodation-dependent effects would vary with target distance .We may therefore ask if the effects of spectacle lens could affect the way the eye perceives size and distance? This size-matching experiment was designed to explore this question.

3.2.5.1 Procedure

The same size-matching method as described in section 3.1.1 was used. The standard targets were placed at 4 different distances: 3m, 1m, 0.5m and 0.25m. The variable comparison target was situated at 2 m.

At each distance of the standard target, 10 matches were made for each subject under 2 conditions: when subjects wore spectacle correction and when they wore contact lens correction. (Random sequence of condition)

3.2.5.2 Subjects

A total of 8 subjects participated in this experiment. All except 1 subject had low or moderate myopia. All were experienced contact lens wearers.

Table 3.7 indicates the spectacle and contact lens prescription of the subjects.

Subject	**Contact lens Rx & VA**	**Spectacle RX & VA**	**Vertex Distance**
N	RE-2.25DS VA6/6 LE -2.00DS VA6/6	RE -2.25DS VA6/6 LE -2.00DS VA6/6	12 mm
CL	RE -3.5DS VA6/6 LE -3.50DS VA6/6	RE-3.75/-0.50x180 VA6/6 LE -3.5/-0.25DCx180VA6/6	12 mm
GOH	RE -4.00DS VA6/5 LE -4.00DS VA6/5	RE -4.25DS VA6/5 LE -4.25DS VA6/5	12 mm
CTP	RE -6.75DS VA6/5 LE -7.75DS VA6/5	RE -7.25DS VA6/6 LE -7.25DS VA6/9	10 mm
M M	RE -2.00DS VA6/6 LE -1.50DS VA6/6	RE -2.00DS VA6/6 LE -1.50DS VA6/6	10 mm
FT	RE -3.00DS VA6/6 LE -2.75DS VA6/5	RE -3.00/-0.25x85 VA6/6 LE -2.75DS VA6/5	10 mm
R	R E R G P VA6/6 L E R G P VA6/6	RE -5.5/-1.25x180 VA 6/9 LE -5.5/-1.00x180 VA6/9	10 mm
TMY*	R E R G P VA6/6 L E R G P VA6/6	RE-12.50DS VA6/9 LE -12.25DS VA6/9	10 mm

*Table 3.7: The contact lens and spectacle prescription of the subjects. All subjects wore soft contact lens except for R and TMY. * Indicates the subject had high pathological myopia. RGP (Rigid gas permeable contact lens)*

The was 1 particular subject (TMY) who had high pathological myopia. Ophthalmoscopy revealed stretching and thinning of the retina, and full spectacle-corrected vision was 6/9. There was also slight partial visual field loss in both eyes. Since the myopia of this subject was high (see Table 3.7) her

result is discussed separately and is excluded in the computation of the composite mean.

3.2.5.3. Results

The composite mean of perceived angular size of the comparison target for 7 subjects (excluding subject TMY) are shown in figure 3.16. Individual subject results are shown in figure 3.17.

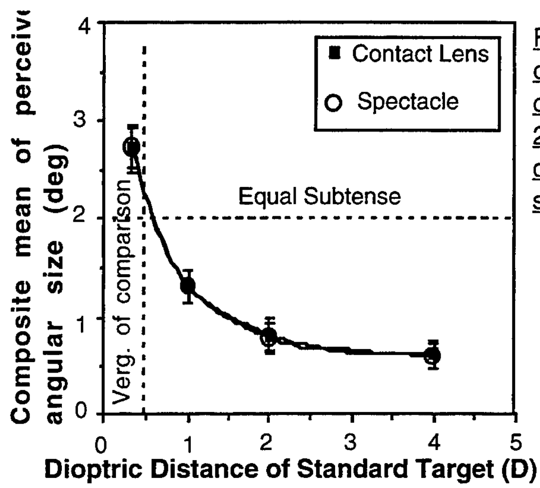


Figure 3.16: Composite mean of perceived angular size of comparison target (situated at 2m) as a function of the dioptric distance of the standard target.

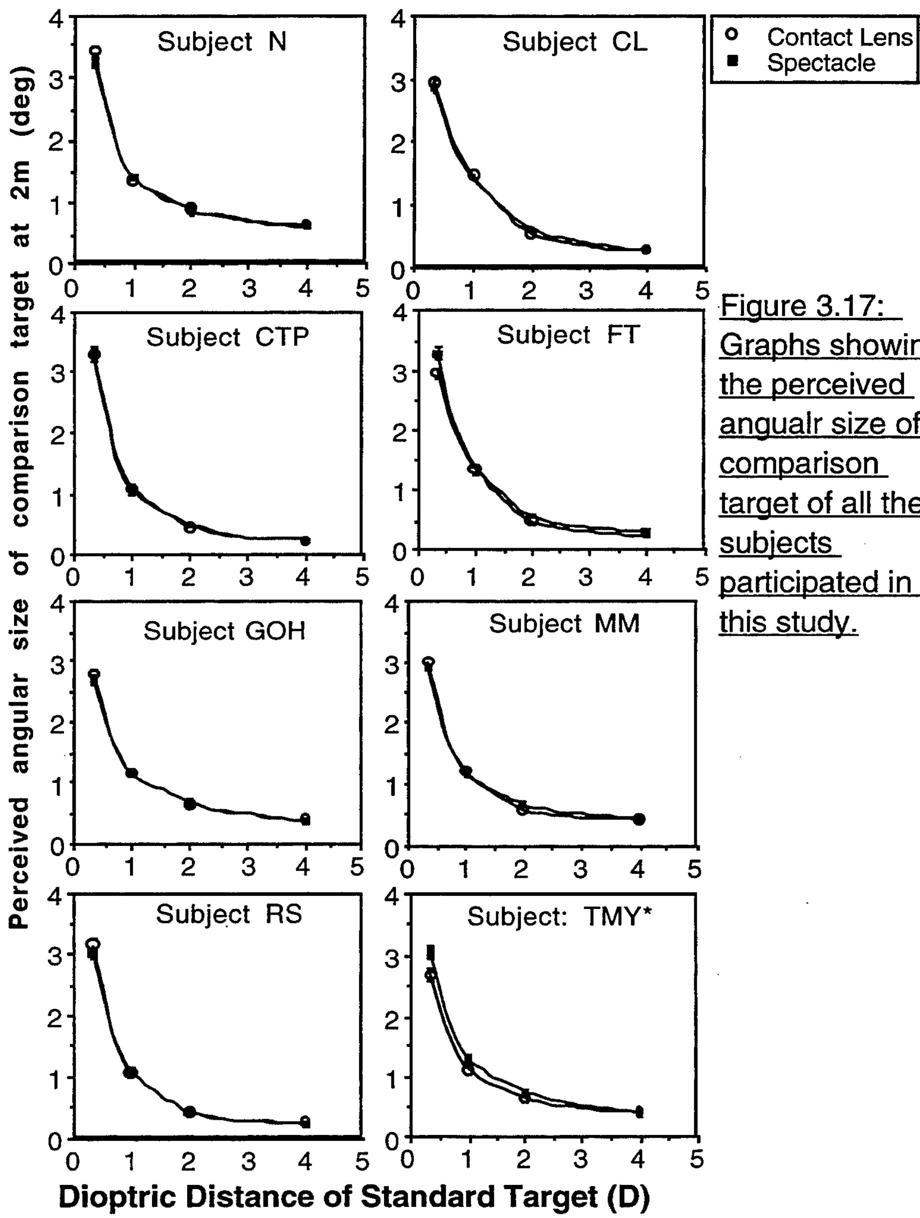


Figure 3.17: Graphs showing the perceived angualr size of comparison target of all the 8 subjects participated in this study.

3.2.5.4. Discussion

The 2 graphs in figure 3.16 indicate that the composite means of the perceived angular size for the 7 subjects under the 2 viewing conditions coincided closely. Moreover, a paired 2 tailed t-test showed that there was no significant different between the 2 composite means of angular size perception under the 2 viewing conditions at all distances of the standard target. ($p = 0.65$, 0.61, 0.06 and 0.12 for distances of 3m, 1m, 0.5m and 02.5m respectively)

All subjects except for subject TMY showed more or less the same kind of size perception under the 2 viewing conditions (Figure 3.17)

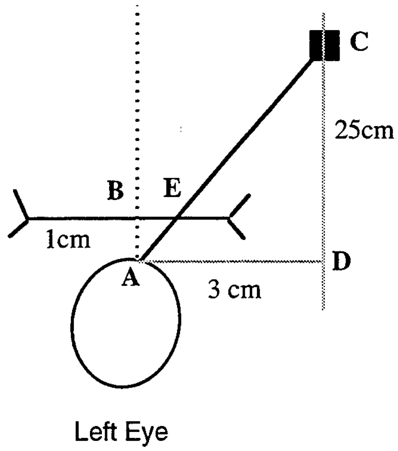
Subject TMY had high myopia (RE -12.50DS, LE -12.25DS) and under spectacle correction, she perceived the targets as larger in angular size than in contact lens correction. This difference in size perception happened when the standard target was placed at 3m, 1m and 0.5m. At 0.25m, there was no difference in the size perception. ($p=0.00$ for 3m, 1m and 0.5m, $p = 0.198$ for 0.25m)

There might be 2 reasons why she perceived the targets as smaller when she wore spectacle:

1. Reduction in ocular accommodation under spectacle correction for myopia as compared to contact lens correction. (Section 2.2.3) However it can be argued that the contact lens prescription should take into account the vertex distance of the spectacle correction during fitting. Thus such difference in ocular accommodation may not be too great. ($A \approx -L(1+2aK)$, where A = Accommodation, L = Vergence of the target, a= vertex distance, and K = ocular correction. i.e. the biggest difference in accommodation , $-L2ak$, occurs for biggest L, -4D. Thus $-L2aK \approx 1D$)

2. The base-in prismatic effect ($P = cF$) induced when she fixated anywhere nearer than infinity. We know that base-in prism stimulates divergence and hence could result in macropsia. If it was the case, then more macropsia would result for nearer distances for this particular subject. However, when the standard target was at 0.25m, she did not show any difference in size perception. ($p = 0.198$) This was puzzling, but the possible reason might be

due to suppression of one eye during near fixation. Suppression might happen because of base-in prismatic effect induced: (see figure 3.18)



DC = Target's distance from the eye, = 25cm
AD= Half pupillary distance, = 3 cm
AB = Vertex distance, =1 cm
BE = Calculated to be 0.12cm.

P = cF, and c=0.12cm and F = -12.25D, thus
P = 1.5 prism base in.

Figure 3.18: Schematic diagram (not to scale) showing the approximate calculation of prism power, P, subject TMY's left eye experienced when she viewed the 0.25m standard target. Pupillary distance was assumed to be 6 cm

When we took into consideration the prismatic power experienced by the right eye (F = -12.5DS), the total estimated prismatic power induced would be (1.5 x 2) = 3 prism base-in.

3.2.5.5 <u>Conclusion</u>

In majority of our subjects who had low to moderate myopia, there was no difference in size perception when they wore their spectacles and their contact lens corrections. However for one subject with very high myopia, size perception was generally bigger with spectacle correction as compared to contact lens correction. Such macropsia was possibly due to the base-in prismatic effect during near fixation.

3.3. <u>Measurement of accommodation</u>

As mentioned in section 3.1.2., two experiments were conducted to measure accommodation of the eye under the different viewing conditions. The aim was to find out if there was any change in accommodation when there was a difference in size perception under the different viewing conditions.

3.3.1. Accommodation with and without an artificial pupil

In order to confirm that less accommodation was exercised with the 1 mm artificial pupil, a direct study of the accommodation response as a function of target distance was made.

3.3.1.1. Subjects

4 subjects (LH, S, A and N) participated in this experiment. Refer to Table 3.1 for their optometric data.

3..3.1.2 Procedure

Accommodation was recorded with a Canon R-1 Autorefractor. This instrument has been widely used in accommodation studies and has been shown to have adequate validity and reliability (Matsumura et al., 1983; McBrien and Millodot, 1985). Its great advantage is that the refractive state of the eye can be recorded while targets are viewed without obstruction through a large beam splitter on the top of the instrument. Since the instrument needs a roughly 3 mm pupil to provide correct measurements, a normal artificial pupil could not be used. Instead the 1 mm- diameter artificial pupil was drilled in Kodak Wratten 87 filter material: this is opaque in the visible but transparent to the infra-red wavelengths used by the auto refractor.

Subjects were positioned on the chin rest of the instrument and viewed the same standard and comparison targets as before. To provide a more complete record of the response/stimulus curve, responses to additional square standard targets subtending 2 degrees at distances of 0.67, 0.50, and 0.25 m were also recorded. At least 10 measurements of accommodation were taken for each target distance and pupil condition.

3.3.1.3 Results

The results found are summarised in Table 3.8 and figure 3.19. The natural pupil was about 3-5 mm under the observing conditions in use.

DISTANCE (M) WITHOUT AP	Subj. LH ACCM (D)	Subj. S ACCM (D)	Subj. A ACCM (D)	Subj. N ACCM (D)	MEAN ACCM (D)
9	-0.25	0.79	0.17	0.05	0.19
3	0.26	0.44	0.16	0.43	0.32
1	0.08	0.65	0.4	0.9	0.51
0.67	0.59	1.14	0.71	1.12	0.89
0.5	1.32	1.6	1.34	1.65	1.48
0.33	1.9	2.42	2.15	2.59	2.27
0.25	2.83	3.39	2.83	3.33	3.1
0.2	3.78	3.91	3.6	4.01	3.83
Distance (M) WITH AP					
9	0.37	1.58	0.6	0.7	0.81
3	0.77	1.61	0.12	1.3	0.95
1	0.52	1.6	0.26	1.28	0.92
0.67	0.75	1.91	0.22	1.31	1.05
0.5	0.8	2.15	0.2	1.32	1.12
0.33	0.4	1.37	1.17	2.11	1.26
0.25	0.78	1.64	1.21	1.69	1.33
0.2	1.07	1.99	0.7	2.16	1.48

Table 3.8: Monocular, steady-state accommodation responses of 4 subjects to 2-degrees square standard targets at the distances indicated. Top: natural pupils. Bottom: with 1 mm-diameter artificial pupil.

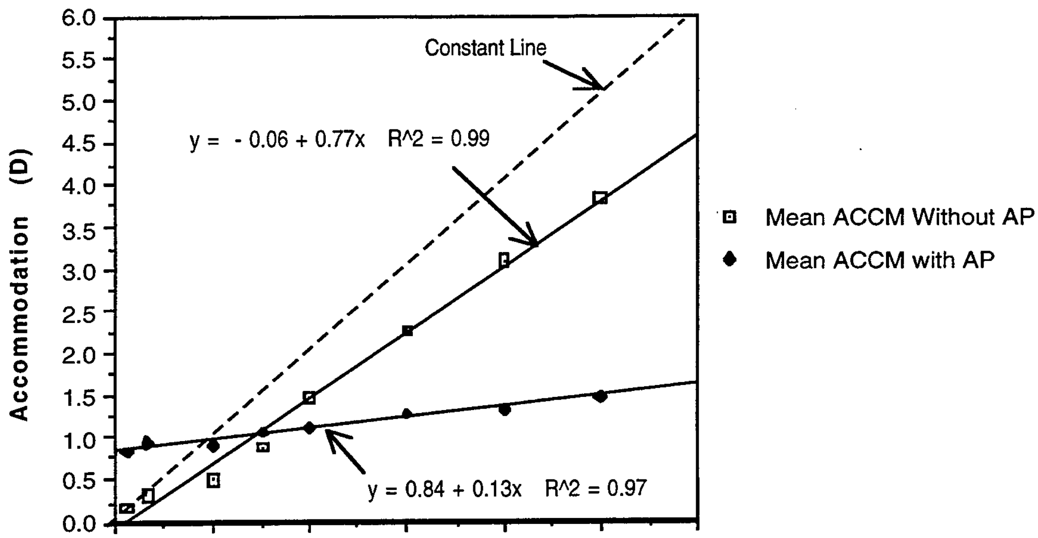


Figure 3.18: Mean levels of accommodation for when viewing 2-degrees square standard targets at the dioptric distances (vergences) indicated. Four subjects; monocular observation; no restriction on field of view. Diamond symbols: 1 mm artificial pupil. Square symbols: natural pupil

3.3.1.4. <u>Discussion</u>

It is obvious that, as expected, changes in the level of accommodation with target distance were much smaller with the artificial pupil. With the reduced pupil the level of accommodation remained close to the tonic or resting level which also manifested itself as the dark focus (Hennessy et al., 1976; Ward and Charman, 1987).

The findings of the experiments in section 3.2.2.4 and this section were interesting from several points of view. First, with the smaller pupil, as was evident from figure 3.6 and 3.7, errors in accommodation (focus) were generally larger and yet the errors in size estimation were smaller (i.e. the apparent size is closer to 2 degrees). On the "inappropriate accommodation" or "zoom lens" hypothesis (Roscoe, 1985, 1993), larger size judgement errors would be expected. On the other hand, if as some authors had suggested the reduction in size was related to the accommodative effort, i.e. to the neural signals that innervate the ciliary body (Lockhead and Wolbarsht, 1989) a smaller size reduction would be expected with the small pupil, as observed.

It might be objected that the failure to observe the larger size judgement errors predicted by the "inappropriate accommodation" hypothesis was in some way associated with the position of the artificial pupil, which was located some 15 mm in front of the eyes rather than in the plane of the natural pupil (Biersdorf and Baird, 1966; Tucker and Charman, 1975; Marsh and Temme, 1990). As discussed in section 2.2.1 the associated changes in the path of the chief ray for the case of under-accommodation for near objects tend to cause the retinal image to be larger than it would be for the same state of defocus with the natural pupil (see figure 2.1). This would tend to lessen the size reduction in comparison with that observed with the natural pupil. However, with all errors of focus being less than 4 D, we found that the changes in size associated with this effect would always be expected to be less than 10%, whereas, for example, the 0.20 m standard target was seen as being almost twice as large with the small pupil at 15 mm in front of the eye than with the natural pupil (see appendix 3.1). If the pinhole was moved well in front of the eye the effect was, of course, much larger as was found by Biersdorf and Baird (1966).

Other possible reasons why size change effects might be smaller with the artificial pupil were the partial restriction of the field-of-view, and an increase in the depth-of-focus caused by the artificial pupil. Manipulation of the depth cues in a scene is known to affect size and distance judgements. (see section 1.2.4.2.2). It could be agreed, for example, that with monocular viewing and the large depth-of-focus conferred by the small pupil, the visual world for a static observer effectively resembles a flat, two-dimensional photograph. Under such circumstances and in the absence of cues such as overlap, the square standard and comparison targets would be matched largely on the basis of angular subtense, as observed. (Figure 3.6 and 3.7).

3.3.1.5. Conclusion

With the 1 mm artificial pupil, changes in the level of accommodation with respect to target distance were much smaller than with natural pupil. With the natural pupil, the level of accommodation response was closer to the stimulus, though accommodation lag was apparent.

In the monocular size matching experiment in section 3.2.2.4, the law of visual angle had a greater effect on size perception when the subjects viewed through the 1 mm artificial pupil. Thus we can deduce that the modest depth-of-focus and accurate accommodation response to the target's distance associated with

the natural pupil caused size perception to be more strongly influenced by the law of size constancy. On the other hand, the large depth of focus and the absence of accurate accommodative response associated with the 1 mm artificial pupil caused size perception to move closer towards the law of visual angle.

3.3.2 Accommodation during monocular and binocular viewing

Some authors suggest that monocular viewing conditions biasses accommodation in the direction of the dark focus. According to Hale (1990), Roscoe et al (1976) measured binocular and monocular accommodation while subjects viewed a disk of light subtending a constant visual angle but varying in distance between 0.25 and 4 meters. For the distant viewing condition of 4 meters, shifts from binocular to monocular viewing were accompanied by reliable shifts in accommodation. In addition, as accommodation shifted inward toward the dark focus, there was a reliable reduction in judgements of the apparent size of the disk.

Significant differences in monocular and binocular size judgements were also demonstrated by Meehan and Triggs (1988). Their subjects performed a size-matching task by adjusting the focal length of the lens of a 35 mm camera. Subjects viewed 4 natural scenes directly either monocularly or binocularly. They then viewed the same scenes through the camera and adjusted the focal length of the lens until the apparent size of the "displayed" image matched the size of the image viewed directly. The focal length of the camera lens was then converted to magnification values. The results were analysed to evaluate the effects of viewing condition. The results indicated that the amount of magnification chosen by the subject to match the monocular view was significantly less than for scenes viewed binocularly. Thus, monocular vision resulted in smaller apparent sizes of the 4 scenes compared to binocular vision.

Holway and Boring (1941) have also shown that distant objects appear smaller when viewed with one than 2 eyes.

In our experiments in section 3.2.2, the subjects matched the size of a 2 degree constant subtense standard target situated at 0.20, 0.25, 0.33, 0.50, 1 and 3 m with a comparison target at 2 m under binocular and monocular viewing conditions. The results also indicated that under monocular viewing condition, there was a smaller apparent size when compared to binocular viewing condition. The reduction in

apparent size was more marked at nearer distance than farther distance. (Refer to figure 3.6.)

Roscoe (1985) had suggested that when viewing an object with 1 eye closed, the closed eye tend to lapse towards its resting point of accommodation and draw accommodation of the open eye inward by the same amount. (Roscoe 1977, 1979). Is the reduction in apparent size under monocular viewing really due to the pulling of accommodation of the seeing eye towards the resting point accommodation of the occluded eye? This experiment aimed answer these questions.

3.3.2.1. Procedure

Accommodation was measured on the right eye by the Canon-R1 auto refractor when the subject fixated a 6/6 illiterate E at 6m in binocular and monocular viewing conditions. Measurements were taken continuously over a period of 3 minutes. The first measurement was taken immediately the subject fixated the letter. The subject was instructed to try to keep the fixation target as clear as possible throughout the 3 minutes. In monocular viewing, the subject's right eye was occluded using an occluder. The 2 viewing conditions were measured randomly.

It could be argued that we are not measuring accommodation but the objective distance refractive errors of the right eye instead. This is true, but any change in "refractive errors" under binocular and monocular viewing conditions must be ascribed to a change in accommodation, since measurements were made in the same constant environment. Thus for simplicity, we are assuming that accommodation was measured.

After measuring the accommodation at 6 m, the procedure was repeated at 0.50 m. This time, the fixation target was a N5 letter situated on the mid-line of the subject.

Throughout the whole experiment, the room and the fixation target's luminances were constant.
The tonic accommodation level of the subjects were then measured on a different day from the procedure described above. We assumed that the tonic accommodation of a person remained constant over a period of time. (The tonic

accommodation levels of all subjects were measured, except subject P who was not available)

The tonic accommodation/dark focus of the left eye of each subject was measured by the Canon R-1 auto refractor over a period of 3 minutes after 5 minuets of dark adaptation. Complete darkness was achieved by covering the subject and the auto refractor with a large piece of black cloth in a dark room. The subjects were instructed to keep their eyes straight and to stare into the darkness in front during measurements. An average of 2 readings of the dark focus was obtained in every 10 seconds over the 3 minutes.

3.3.2.2. Subjects

6 subjects participated in this experiment. (ages between 20 to 25 years, 4 males and 2 females). All had visual acuity equal or better than 6/6 and were non spectacle wearers or contact lens wearers.

3.3.2.3. Results

The results at 6 m for each subject are summarised in figure 3.20.

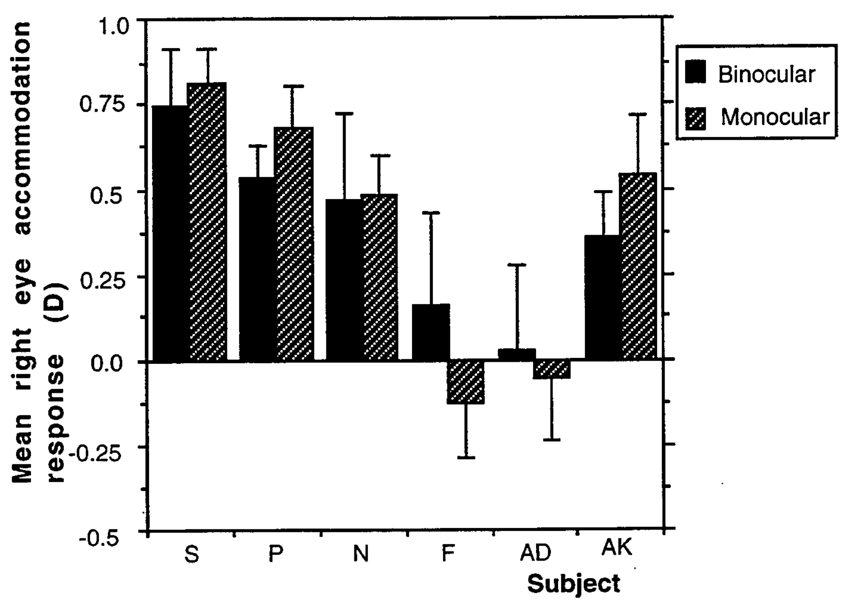


Figure 3.20: Comparison of the mean right eye accommodation response over a period of 3 minutes under the 2 viewing conditions(binocular, monocular) at fixation distance of 6 m among the 6 subjects. Positive values of response mean that the right eye was myopic or showed an increase in accommodation.

The t- test (2 sample assuming equal variance) was used for each subject to test if there was any significant difference between the mean responses for the two viewing conditions. The p values for each subject are shown in Table 3.9.

Subject	Binocular vs Monocular
S	$p<0.001$
P	$p<0.001$
N	$p>0.05$
F	$p<0.001$
AD	$p<0.05$
AK	$p<0.001$

Table 3.9: p values for the 2 tailed paired t-test results to test if there is any significant difference in response of the 2 viewing conditions at 6m. $p>0.05$ indicates that there is no significant difference.

Of the 6 subjects, only 1 subject (N) showed no significant difference in the mean accommodation when comparing binocular viewing with the monocular viewing at 6m.

From the results obtained, 4 subjects (S, P, N and AK) showed that there was indeed an increase in mean accommodation in monocular viewing as compared to binocular viewing.

Even though most subjects showed that a significant difference in accommodation between the 2 viewing conditions, the magnitude of this difference was very small. The difference between the 2 composite means for the 6 subjects was only 0.01D and a paired 2 tails t-test showed that this was not significant. (See to figure 3.21)

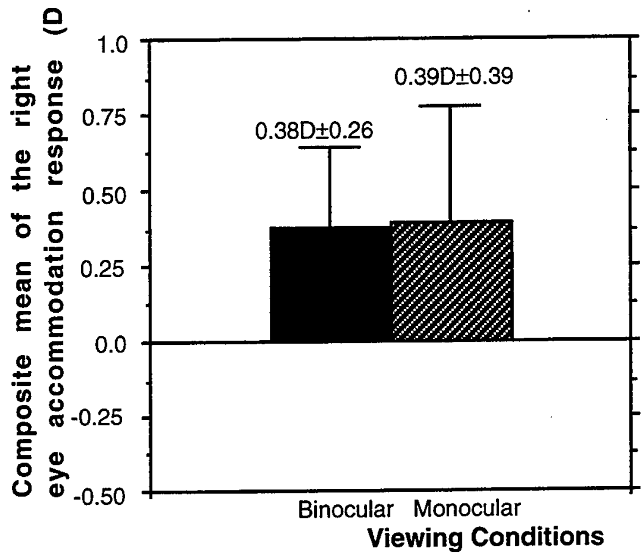


Figure 3.21: Composite means of all the 6 subjects right eye accommodation response under binocular and monocular viewing conditions. The fixation target was at 6m (p = 0.92, means there was no significant difference between the 2 composite means)

The results at 0.50 m for each subject are summarised in figure 3.22.

The t-test (2 sample assuming equal variance) was used in each subject to test if there was any significant difference in the mean accommodation between the 2 viewing conditions. The p values for each subject were shown in Table 3.10.

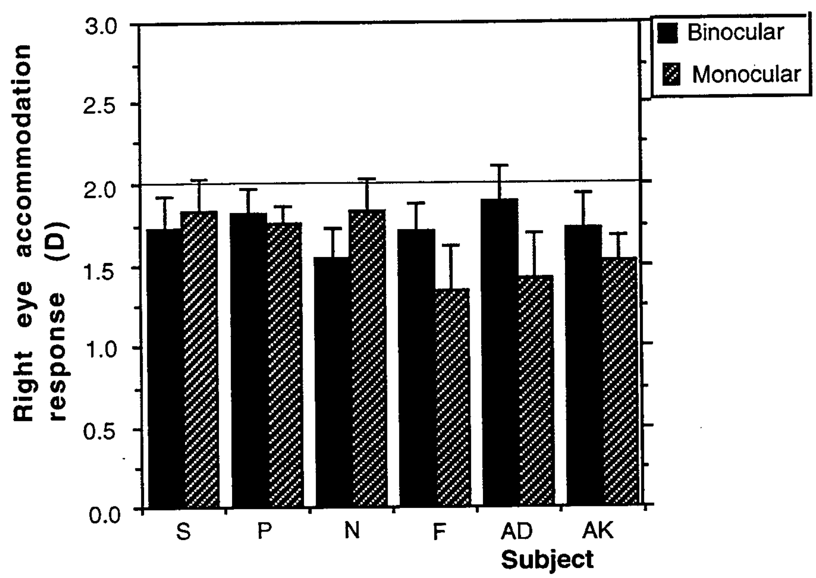


Figure 3.22: Comparison of mean accommodation response of the right eyes over a period of 3 minutes under the 2 viewing conditions (binocular, monocular) at fixation distance of 0.50m among the 6 subjects.

Subject	Binocular vs Monocular
S	$p<0.05$
P	$p<0.001$
N	$p<0.05$
F	$p<0.001$
AD	$p<0.001$
AK	$p<0.001$

Table 3.10: Paired 2 tailed t- test results to test if there is any significant difference in the 2 pairs of viewing conditions at 0.50m. $p>0.05$ indicates that there is no significant difference.

From the t-test results, all subjects showed that there was a significant difference in the mean accommodation between binocular viewing and monocular viewing

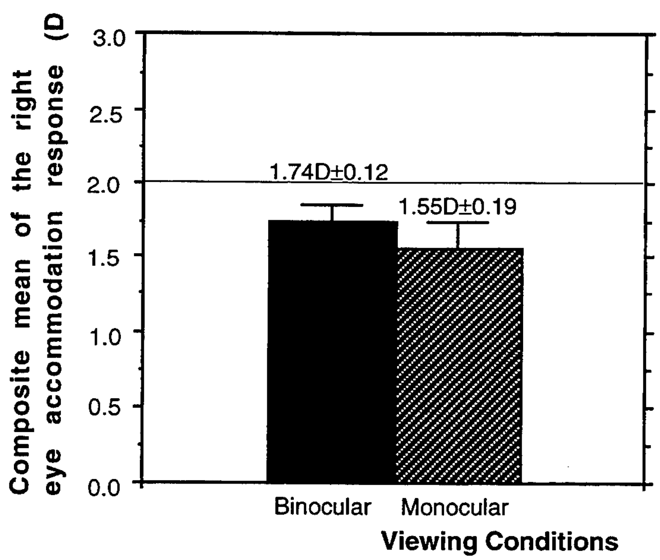


Figure 3.23: Composite means of all the 6 subjects right eye accommodation response under binocular and monocular viewing conditions. The fixation target was at 0.5m ($p = 0.08$, means there was no significant difference between the 2 composite means)

As in the case of the 6 m fixation distance, the magnitude of the change in the mean accommodation was very small (see figure 3.23). The composite reduction in the mean accommodation from binocular viewing to monocular viewing is 0.19D A paired 2 tailed t-test showed that the 2 composite means were not significantly different ($p = 0.08$) .

The tonic accommodation level of each subject is shown in table 3.11: Subject N was probzbly slightly undercorrected,

Subject	Tonic Accommodation level/Dark Focus (D)
S	1.65±0.60
P	N.A.
N	1.95±0.57
F	1.94±0.54
AD	-0.17±0.26
AK	1.01±0.19
Mean	1.28

Table 3.11: Table showing the tonic accommodation level of the subjects. (Subject P was not available)

Figure 3.24 summarises the results for each subject in this experiment.

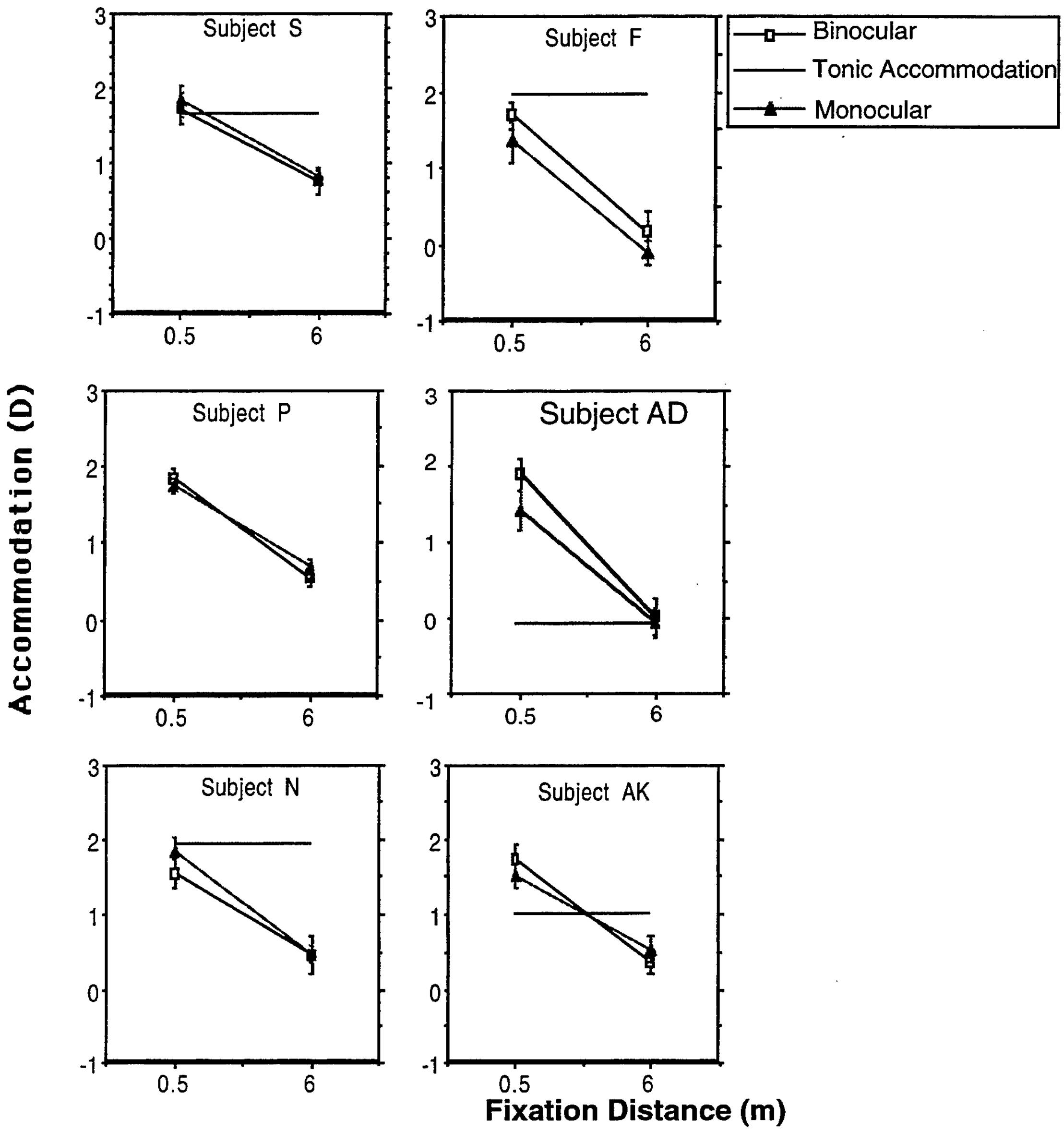


Figure 3.24: Summary of results. The accommodative response of the subject's right eye under binocular and monocular viewing condition at 2 fixation distances. (0.5m and 6m) The horizontal line was the tonic accommodation level of the subject. (Subject P's tonic accommodation was not available, and Subject AD's tonic accommodation was negative)

3.3.2.4. Discussion

In the absence of adequate visual stimulus, accommodation adopts an intermediate position of ≈ 1.00D depending on the method of measurement. (Rosenfield et al, 1992). Leibowitz and Owens (1975a, 1975b) used a laser optometer to measure the accommodative response in darkness and obtained

mean values of ≈ 1.50D. Rosenfield (1989) compared the levels of tonic accommodation obtained using a laser optometer with those values recorded using an objective, open field, infrared optometer in total darkness. Mean tonic accommodation values of 2.01 D and 1.28 D were recorded for the laser and infrared optometers, respectively. The mean dark focus of our 5 subjects was 1.28 D. This was very close to Rosenfield (1989) level of tonic accommodation as recorded by an infra-red optometer.

When a person closes one eye, the occluded eye will be in complete darkness. According to Roscoe (1985), the occluded eye then lapses towards its resting point drawing the accommodation of the open eye inward by the same amount, thus causing micropsia when a distant object was viewed monocularly.

However, our experiment results show that for distant viewing there is no significant difference in the composite mean accommodation between binocular and monocular viewing. Though there was variation in the subjects' response

For near fixation at 0.50 m (vergence of 2.00D), 5 subjects (P, N, F, AD and AK) showed a reduction in accommodation when the target was viewed monocularly when compared to binocular viewing.(mean change of 0.19D under monocular condition). This could be interpreted as supporting Roscoe's hypothesis, because the dark focus (resting point of accommodation) of our subjects is less than 2.00 D. (i.e. the RPA of the closed eye was less than the vergence requirement of 2.00D in the open eye, thus pulling the accommodation of the seeing eye farther away). However a much more likely explanation of the modest difference in accommodation levels is the absence of convergence drive to the accommodation system under monocular conditions, which be expected to reduce the accommodation response.

In fact it is clear that it is difficult to separate the effects of differences in accommodation from those of convergence when making monocular/binocular comparisons of size perception.

3.3.2.5. Conclusion

We conclude that, in most of our subjects, accommodation was slightly different under binocular and monocular viewing for distance or near target. This was probably due to the convergence-driven accommodation associated with binocular viewing, although some of the individual differences may have been associated with slow drifts in accommodation, since the monocular and binocular observation were separated in time. Such differences were small. (0.07D to 0.28D for distant viewing and 0.07D to 0.48D for near viewing)

In view of the small magnitude of the monocular/binocular accommodation difference, we further conclude that any reduction in apparent size with monocular view at far viewing distances (e.g. the moon appears smaller under monocular viewing) is not likely to be due to the pulling of accommodation of the seeing eye by that of the occluded eye. The reduction in apparent size may be perceptual in origin.

3.4. General Conclusion

The results of these experiments are interpreted as indicating that changes in apparent size as function of distance are unlikely to be caused by accommodation-dependent changes in the size of the retinal image. (see particular the after-image study of section 3.2.4 and the monocular/binocular comparison of section 3.3.2) Although we regard our experiments as exploratory rather than definitive, they result in the following conclusions for the apparent sizes of objects which all subtend the same angle at the cornea but which differ in the distance in the range 0.2 to 3 m:

1. The way we perceive size is governed by 2 laws: The law of size constancy and the law of the visual angle. If there is a comparison target and a standard target in any size judgement situation, the perceived size can be approximately described by the equation: $\mathbf{C_V\theta_V + C_c\theta_c = \theta_{OBS}}$. The weighting constants, $\mathbf{C_V}$ and $\mathbf{C_c}$ will vary under different viewing conditions. In a viewing condition which favours the law of size constancy we will expect a higher $\mathbf{C_c}$ constant, and a higher $\mathbf{C_V}$ constant if the viewing condition favours the law of the visual angle. An increase in the $\mathbf{C_c}$ constant will follow by a decrease in $\mathbf{C_V}$ constant and vice versa. If $\mathbf{C_c} > \mathbf{C_V}$, the law of size constancy plays a more significant role than the law of the visual angle in our perception of size , and vice versa. Table 3.4 shows that, as the distance cues are reduced, $\mathbf{C_c}$ diminishes and $\mathbf{C_V}$ increases.

2. Apparent angular size reduction for near objects is greater when binocular, rather than monocular observation is employed (i.e. with monocular view apparent size is affected more by the law of the visual angle, and less by the law of size constancy)

3. Angular size reductions are greater when the natural pupil (3 to 5 mm) is used than with a 1 mm artificial pupil. Accommodation accuracy is reduced with the small pupil and, correspondingly, less accommodative effort is made to view near targets at vergences greater in magnitude than the tonic accommodation of the subjects.

4. Masking the field-of-view to eliminate cues as to the relative distances of the standard and comparison targets reduces changes in apparent angular size with both natural and artificial pupils.

5. Trials with after-images suggest that in these experiments the size of the optical image on the retina of all the standard targets was constant within about ± 10%. Any changes were in fact probably smaller than this but the limited precision of the matching technique did not allow a more accurate estimate.

6. Different instructions affect the way we perceive size: "True size" and "picture image" instructions tend to favour size constancy and "angular size" instructions tend to favour law of visual angle. "True size" instructions were used for most of the experiments.

7. There is no significant difference in size perception between a spectacle corrected and a contact lens corrected myope. Any differences in spectacle magnification with distance appear to have negligible effect, the spectacle magnification affecting standard and comparison target equally. However for very high myopia, there may be a difference in size perception: for one subject spectacle correction produce larger size perception than contact lens correction. This difference may be attributed to the induced base-in prismatic effect produced by the spectacle lens when the eyes failed to look through the optical centre.s

8. There is no evidence to show that accommodation was pulled inward when one eye is occluded. However, in most of our subjects, there was a small significant difference in accommodation between binocular and monocular viewing. We

attribute such small difference to convergence-driven accommodation under binocular conditions.

It is of interest that these results are, in fact, qualitatively very similar to the classic results of Holway and Boring (1941), although the latter studied effects at somewhat greater distances (about 3 to 30 m). (However, they did not specify exactly the type of instructions given to the subjects in matching the standard and comparison targets.) They too found that, in comparison with normal binocular observation, angular size change effects diminished with monocular vision, use of a small artificial pupil and reduction of the field-of-view to the targets alone. Both studies imply that, irrespective of observation distance, apparent visual size becomes more closely related to the angular subtense (i.e. the law of the visual angle) of the object as the viewing conditions become more impoverished.

Although we feel that accommodation-dependent changes in the size of the optical image on the retina are not the source of changes in apparent size, we do not feel that the possibility that innervation to accommodation(and convergence) being a factor in size judgement can be ruled out (see, e.g. Holst and Mittelstaedt, 1950; Richards, 1967; Marg and Adams, 1970; Hochberg, 1972; Lockhead and Wolbarsht, 1989). This possibility therefore deserves further consideration, although it is usually suggested that in humans accommodative effort is of little value as a distance cue (Heinemann et al., 1959; Kunnapas, 1968). The work of Leibowitz and his colleagues (Leibowitz and Moore, 1966; Harvey and Leibowitz, 1967) appears to support this suggestion (together with the probable involvement of convergence) although the use by these authors of lenses to stimulate accommodation introduces spectacle magnification which somewhat enhances the effects observed.

It may be commented that anecdotal evidence suggests that changes in apparent size are not necessarily dependent on the presence of active accommodation, since presbyopes also experience the moon illusion (Lockhead and Wolbarsht, 1989; Kaufmann and Rock, 1989). Further experiments with presbyopes would be of interest.

At the present time, it would be appear that the results of apparent size experiments of the present type are most simply explained in terms of a shift from a regime in cue-rich environment in which size-constancy plays a major role to judgement based purely on angular subtense when cues to distance are minimised (Holway and Boring, 1941).

It is of interest that both size and shape constancy (e.g. Coren and Ward, 1989, Ch. 14) tend to break down in situations where contextual or depth information is meagre. It seems reasonable to assume that such constancies play a role in the judgement of pilots and that the poorer contextual and depth cues provided by the limited resolution and field of night-vision goggles or other indirect imagery might cause problems for pilots (Brickner, 1989; Hart and Brickner, 1989; Foyle and Kaiser, 1991). It may also be that "phenomenal regression to the real object" (e.g. Thouless, 1931; Brunswik, 1944; Forgus, 1966; Stavrianos, 1945) plays some role in faulty judgements of size and distance.

To summarise, the argument that errors in size judgement are related to changes in the physical dimensions of the associated optical images on the retina. appears uncionvincing The errors are much more likely to be perceptual in origin.

In the next chapter, the effect of a looming target on accommodation. will be discussed

CHAPTER 4: LOOMING

4.1 Introduction

As discussed in section 1.3, a number of authors have suggested that an increase or decrease in the angular size of an object at a fixed distance may cause a change in accommodation and convergence (e.g Ittelson and Ames, 1950; Kruger et al., 1985, 1986, 1987; McLin et al, 1988), although others have failed to find such an effect (Alpern, 1958; Morgan, 1968). It is clear that during approach to a relatively distant object, the vergence (reciprocal of distance in metres) may remain essentially at zero, while the angular subtense changes quite rapidly. For example an approach from 200 to 100 m from an object will result in a doubling of the subtense while the vergence remains at 0.01 D or less.: at a flight speed of a modest 200 km/hr this would take a mere 1.8 sec. Thus, in low altitude flight, looming conditions can undoubtedly occur.

There is therefore a good case for studying this phenomenon further, since earlier studies have done little more than to demonstrate the possible existence of looming-induced accommodation changes. No systematic study has`been caried out on the factors that influence the magnitude (if any) of these changes The present chapter outlines some very preliminary work on this problem. It is hoped that it may be possible to amplify this at a later date.

4.2 Methods

4.2.1. Stimuli

Stimuli were generated using NIH IMAGE software on a Power Mac monitor. The basic stimuli and their spatial frequency spectra are shown in fig. 4.1. The software enabled the angular subtense of each stimulus to be varied periodically at a variable rate between about 0 and 1.0 Hz.. The rate of increase and decrease in subtense corresponded to that which would be obtained during approach or recession from the target at uniform speed A size ratio of 1:5 between the smallest and largest images was used in this preliminary study. (Other patterns of angular change can be produced if required). The Gabor function was used to present an essentially single frequency object to the subject. The Maltese cross was employed since it had been used in earlier studies (e.g. Kotulak et al, 1985, 1986, 1987): it has an idiosyncratic spatial frequency spectrum. Lastly the face represents an object of broad spatial bandwidth with a spatial frequency spectrum lacking marked features at any specific spatial frequency. Such a spectrum is shared by a wide variety of natural objects

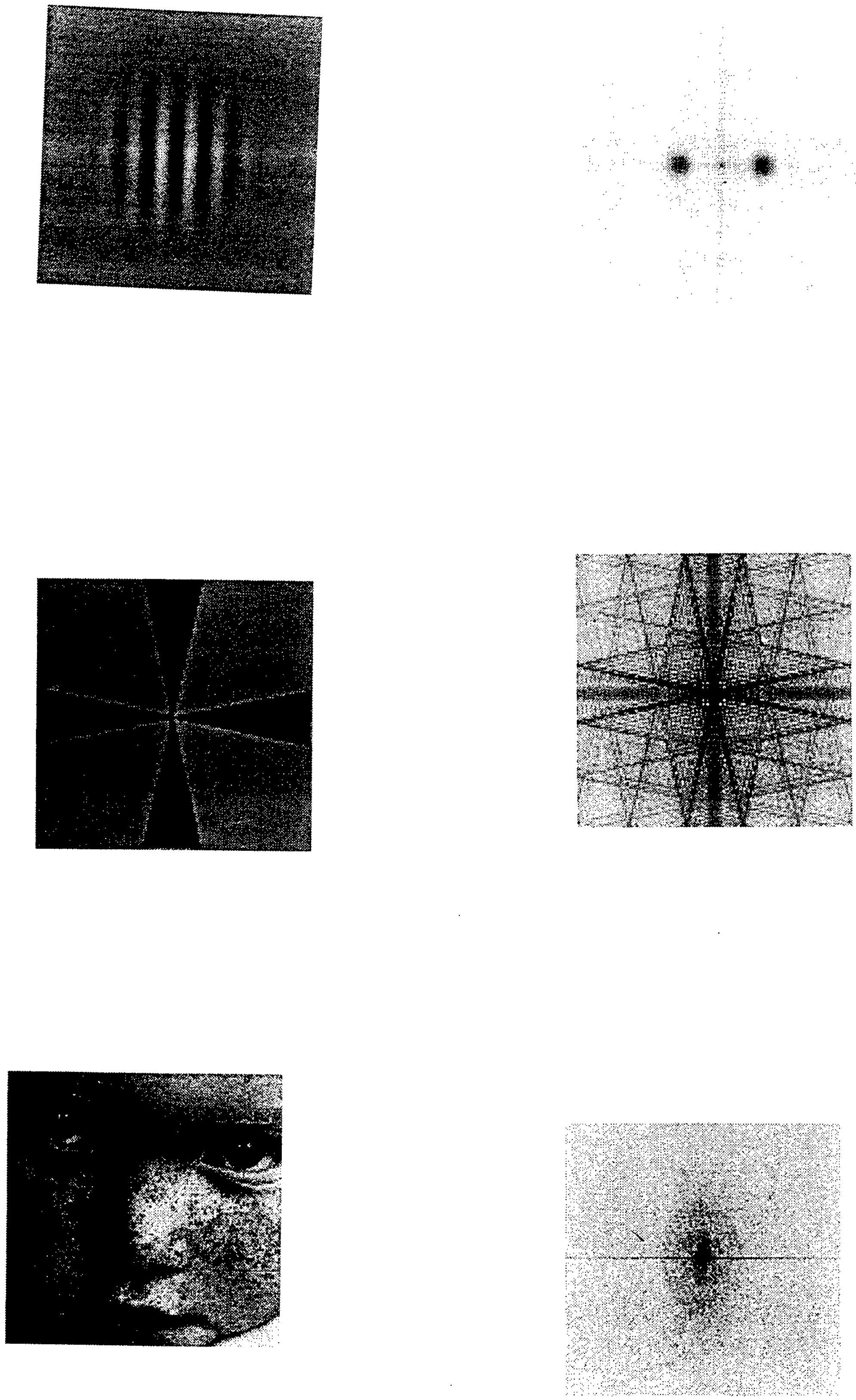


Fig.4.1. *Images used in the looming study (left) , together with their two-dimensional spatial frequency spectra (right).. (Top) Gabor (centree) Maltese cross (Bottom) Face*

4.2.2.Stimulus presentation and recording of accommodation

These stimuli were presented monocularly to the right eye of each subject using the stimulus generator of an SRI optometer (Cornsweet and Crane, 1970; Cornsweet and Clark, 1978). Thus the fixed vergence of the target could be manipulated as required by adjusting the relative positions of the monitor and instrument..

Accommodation was measured using one channel of the optometer and recorded on disk together with the stimulus changes. Calibration was achieved by measuring the response to an abrupt step change in the dioptric vergence of the stimulus.

4.2.3. Results

Typical records to size changes in each of the targets are shown in fig.4.2, It is obvious that substantial looming responses occurred for this subject and that responses were stronger with the broadband targets than in the case of the Gabor with its limited spatial frequency spectrum. Thus it is confirmed that accommodation does undoubtedly occur in response to at least some looming stmuli.

4.3. Planned future programme

A number of properties of the looming stimulus deserve study:

(i) The spatial frequency content of the stimulus. Although obviously this scales with the changing target dimensions it is of interest to see whether, e.g Gabors of comparatively low spatial frequency differ in effectiveness from those of high spatial frequency . It may be that the Gabors, with their rather sparse one-dimesional spectrum are poor stimuli and that broad bandwidth targets are required.

(ii) Target luminance. It is interesting to speculate whether any looming response continues to lower luminance levels than conventional cone-driven accommodation responses. It might be hypothesised that change in target size would still be detectable by the rod system at scotopic levels.

(iii) Starting vergence. A given change in lateral dimensions of the target will simulate a different change in dioptric distance as the initial target distance or vergence changes. For example, a doubling in target size for an initial vergence of 1 D (1 metre distance) simulates an approach to 2 D (0.5 m distance), i.e. a "pseudo" accommodation stimulus change of 1 D. On the other hand, the same size change at 0.5 m (2 D vergence)

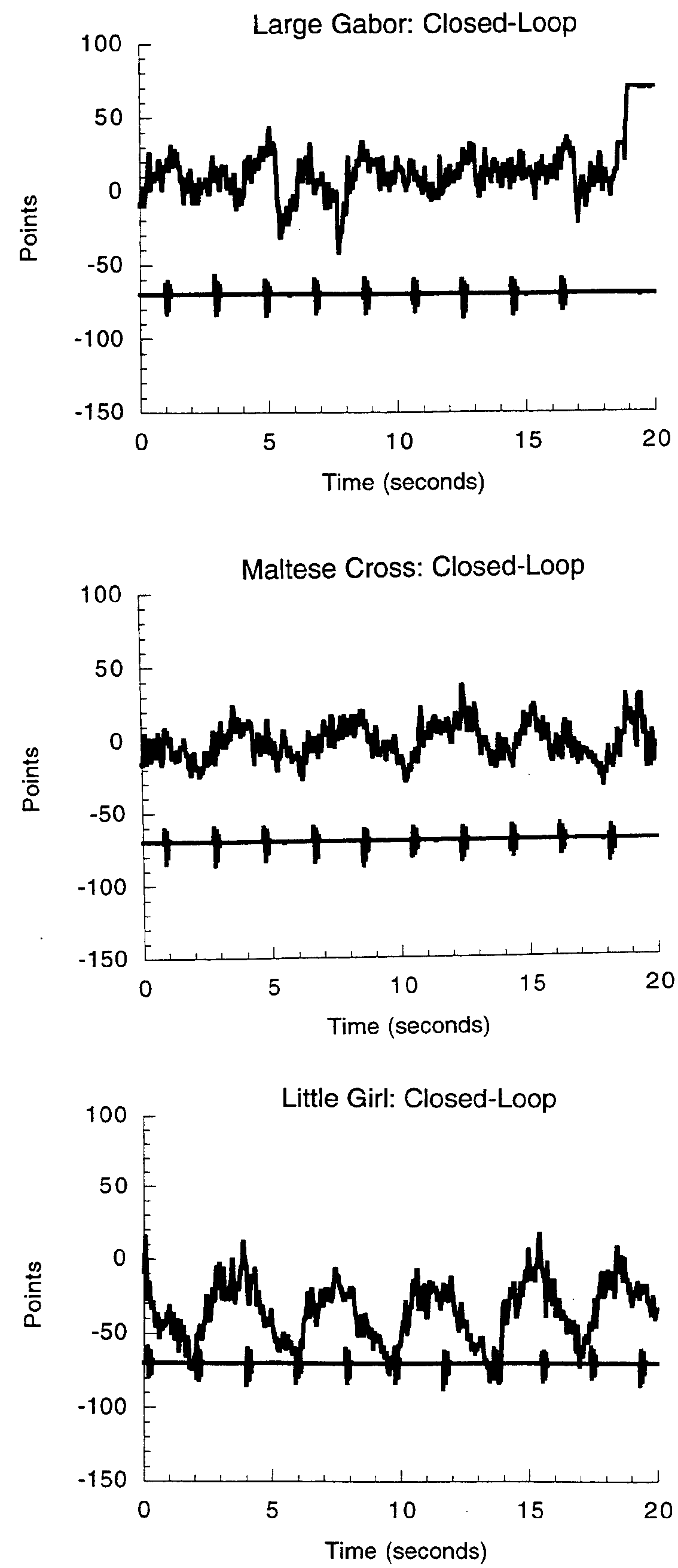


Fig.4.2. Accommodation responses to the three looming targets. In each case size increased by a factor of 5 with the target at an optical distance of 2 D (50 cm)

simulates a movement to 0.25 m (4 D vergence) a "pseudo" stimulus change of 2 D.Will these differences be reflected in the responses?

(iv) The absolute size of the looming target. For normal accommodation responses, the target detail must fall on the fovea , Targets with structure falling on peripheral retina elicit only weak accommodation. It may be speculated that looming responses are also likely to be foveal. The Maltese cross target is a good object to test this, since when it increases in size its central region remains unaffected while its outer parts expand..

(v) The looming range. If the accommodation system responds vigorously to looming the retinal image will blur, since the object has not changed its distance. Thus it may be that in open-loop conditions this blur limits the amount of reponse achieved. For small changes in size accommodation might track the "pseudo" stimulus but the response may saturate for a larger looming range

(vi) The contrast of the target. Although it would be expected that any response would diminish with targte contrast it is not obvious at what level the loss in response might become apparent.

(vii) The experience of the subjects may also be relevant - it may be that relatively naive subjects are requirred if strong responses are to be given and that experienced subjects are too well aware of the nature of the stimulus to respond. It is of course the case that optically any response to size change is inappropriate, so that the stimulus is essentially a perceptual one which may be modified by feedback gained by experience.

(viii) Binocular observation. Since convergence and accommodation are synkinetically linked, looming responses may well differ markedly under monocular and binocular conditions,. Convergence input, for example, may serve to stabilise accommodation under binocular conditions whereas it might itself be driven by looming under monocular conditions. If accommodation did occur under binocular conditions, it could, through its input to the convergence system (AC/A) produce inappropriate convergence as well as retinal image blur with considerable potential for impact on size judgements.

(ix) Closed loop vs open loop. The use of a pinhole pupil to minimise accommodation-induced optical blur will help to clarify the contribution of the various factors to the looming response.

4.4. Summary

The preliminary experiment demonstrates that the available experimental arrangement can give effective information about looming responses and a number of relevant questions suggest themselves. It is hoped that it will be possible to pursue some of these in the futrure.

CHAPTER 5 : ANISO-ACCOMMODATION

5.1 Introduction

In natural viewing conditions, the accommodative demand for each eye is different when the eyes view a target laterally without turning the head. (Refer to figure 5.1) This situation may, for example, arise in the cockpit when a pilot shifts his fixation laterally to read meters containing flight information.

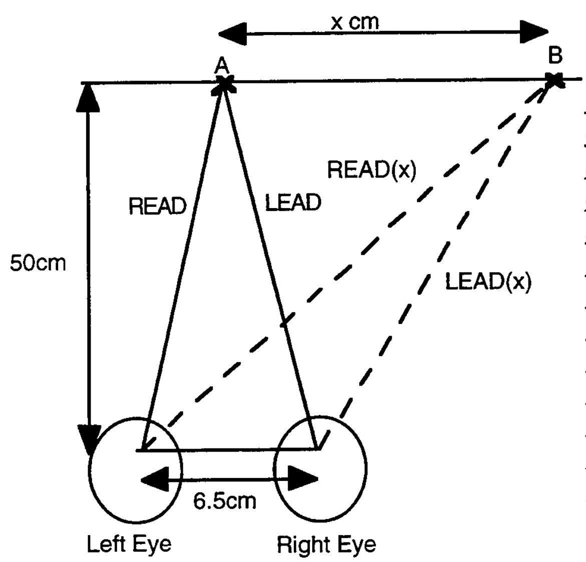


Figure 5.1: Schematic diagram (Not to scale)to show the accommodative demands of both eyes when viewing targets situated at the plane 50 cm from the eyes. "A" is situated on the midline of the 2 eyes, thus READ (right eye accommodative demand) = LEAD (left eye accommodative demand). As fixation is moved away from "A" by "x" cm to "B",the READ and LEAD are now unequal since "B" is nearer to the left eye than the right eye.

It is relatively simple to calculate the accommodative demands of both eyes (distance pupillary distance of 6.5 cm) when the eyes fixate laterally to the left on targets situated on a horizontal plane at vergences of 1D, 2D, 3D and 5D. (i.e. distances of 1.0 m 0.5 m, 0.33 m and 0.2 m) The absolute levels of accommodative demand for each eye are shown in figure 5.2 and the differences between the demands for the two eyes are shown in figure
5.3.

From figure 5.2, it can be seen that when the eyes fixate laterally to the left,
the left eye accommodative demand is greater than the right eye. The reverse is expected if the eyes fixated laterally to the right. As the vergence of the target plane increases the difference in accommodative demand between the two eyes also increases.

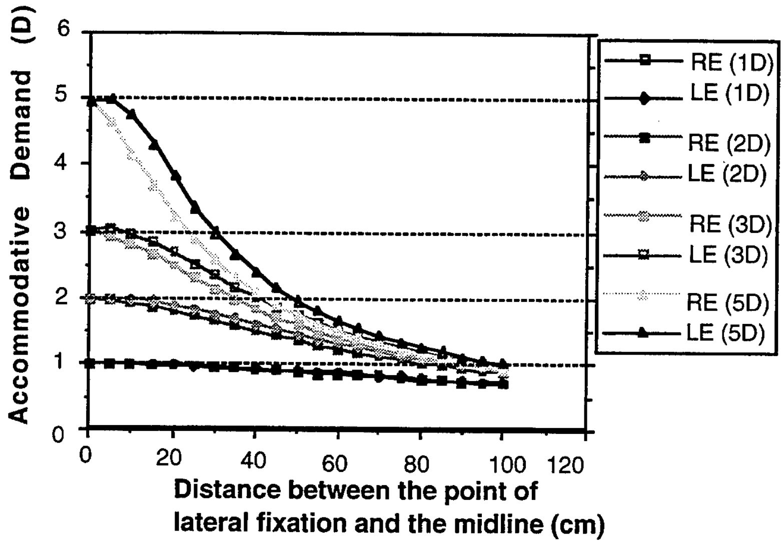


Figure 5.2: Graph showing the calculated accommodative demands of right and left eye (assuming distance pupillary distance of 6.5 cm) when the eyes fixate laterally to the left under 4 vergences of 1D, 2D, 3D and 5D. (i.e. the 4 horizontal planes of fixation are 100 cm, 50 cm , 33 cm and 20 cm from the eyes)

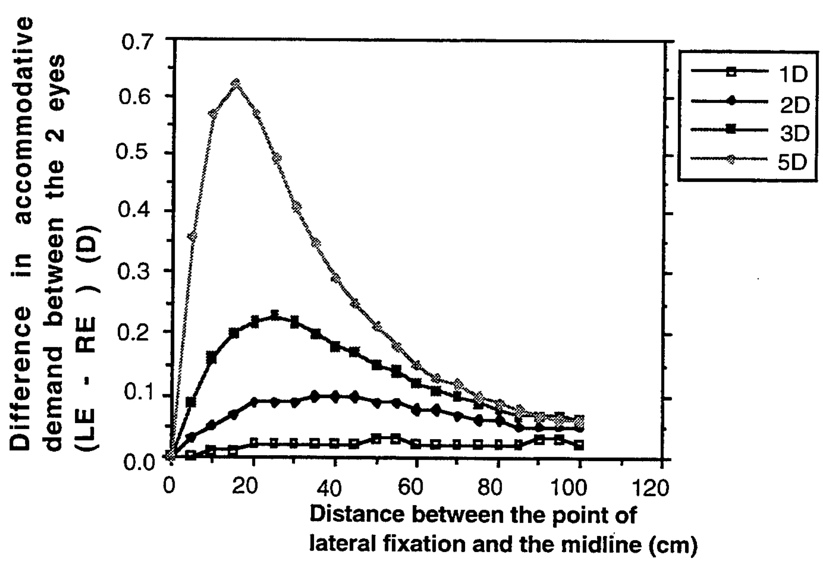


Figure 5.3: Graph showing the calculated difference in accommodative demands of right and left eye (assuming distance pupillary distance of 6.5 cm) when the eyes fixate laterally to the left under 4 vergences of 1D, 2D, 3D and 5D. (i.e. the 4 horizontal planes of fixation are 100 cm, 50 cm , 33 cm and 20 cm from the eyes)

Figure 5.3 shows the exact difference in accommodative demand of the two eyes during left lateral fixation. The greatest difference in accommodative demand is about 0.6D at the 5D vergence plane (i.e. object plane is 0.2 m away) and when the left lateral gaze is about 15 cm from the midline. At the lower vergence of 1D (i.e. object

plane is 1 m away), the difference in accommodative demand is very small, ranging from 0.01D to 0.03D.

In circumstances when the eyes have different accommodative demand, how will the eyes respond? We will try to find out in this chapter.

This study was divided into two parts. In the first part, accommodation of one eye was measured when the other eye's accommodation was stimulated by using concave spheres. In the second part of the study, we determined how the two eyes responded when two aniso-accommodative targets were presented. The aniso-accommodative targets were fusible targets placed at different vergences and each target was seen by one eye.

From a practical point of view the findings may help us to understand how the visual system will respond to possible design or production flaws of such systems as head mounted displays (HMDs), especially those with binocular displays. In a virtual reality environment, there are a variety of accommodative stimuli which are seen through the fixed accommodative stimulus provided by the HMD display. Can the eyes respond to such conflicting accommodative stimuli without causing asthenopia?

The findings may also have significant implications for optometric practice. For example:

1. The effect of the refractive error of one eye if the other is over-corrected with negative sphere or under corrected with positive sphere;

2. The effect of uncorrected ametropia in an eye on its fellow emmetropic eye;

3. The importance of binocular equalisation in refraction;

4. The effect on the accommodative system of an early presbyope who has monovision due to contact lens correction. (Distance prescription for one eye and reading prescription for the other eye).

5. The effect of anisometropia in the young.

5.2 Part 1: Using concave lenses to stimulate accommodation

5.2.1. Method

The subjects viewed binocularly a Snellen 6/6 equivalent letter on a LogMar chart situated 6 m away. The subjects were told to try to maintain clear fixation of the letter throughout the experiment. Accommodation in the right eye (except for subject RS and SB) was stimulated by placing negative spheres in front of the eye (also called the "with lens" eye) at a vertex distance of 12 mm, and the accommodation of the fellow eye (also called the "no lens" eye) was measured with the Canon R1 infra-red auto-refractor. Small steps of accommodation were stimulated progressively by gradually increasing the strength of the negative sphere. The increase in the strength of the negative sphere was stopped when the subjects showed signs of fatigue or their vision was blurred.

The dark foci of the subjects were also measured. Each subject was dark adapted for 3 minutes in a completely dark environment, and the focus of the eyes was measured continuously for another 3 minutes using the Canon R1 auto-refractor.

The dominant eye, and the binocular amplitude of accommodation of each subject were also determined.

The dominant eye was determined by asking the subject to look binocularly at a straight ahead distant target, and then clasping both hands together to aim at the target. While the subject was aiming at the target, one of the eyes was occluded. If the subject reported that he/she was still aiming at the target, then the unoccluded eye was the dominant eye. If the subject reported that the target moved, then the occluded eye was the dominant eye. The procedure was repeated several times and the eye which showed more dominancy was regarded as the dominant eye.

The amplitude of accommodation was measured using a Prince's Rule binocularly The original Prince's Rule was a single rule with distance and optical markings on it. A target was moved along the rule to determine the amplitude (Borish, 1975). It is now modified so that it looks like the letter "Y". One end of the rule rests on each cheekbone, which is very close to being in vertical alignment with the front of the cornea. (Krimsky, 1960).

The subjects (fully corrected for distance) viewed the test chart at some convenient distance. The chart was moved slowly towards the eyes while the subjects attempted to keep the print as clear as possible. When the chart passed inside of the subject's near point (punctum proximum), a blur was reported. The reciprocal of this distance in metres was the dioptric value of the amplitude of accommodation.

5.2.2. Subjects

6 subjects (mean age 23 yrs ± 2.83) participated in this study. All have a VA of 6/6 or better in both eyes, and have normal binocular vision. Subject AW has slight uncorrected myopia. This slight myopia was taken into account when the accommodation was computed.

Appendix 5.1 gives full details of the subjects.

5.2.3 Results

Refer to Appendix 5.2 for detailed individual results. Figures 5.4 to 5.9 indicate the accommodation response of the "no lens" eye (left eye for all the subjects except subject RS and SB) when the "with lens" eye's accommodation was stimulated by negative spheres.

It can be seen that in 3 of the subjects (subject N, RS, and AW), if the "with lens" eye was stimulated with small negative spheres (-0.25DS to -2.00DS) the "no lens" eye's accommodation was also stimulated. With higher spherical power, however, the accommodation tended to relapse towards its "no lens" level.
In the other 3 subjects (SB, S and AD) the "no lens" eye did not show any systematic change in accommodation at any specific level of stimulation on the "with lens" eye.

Figure 5.4: Subject N

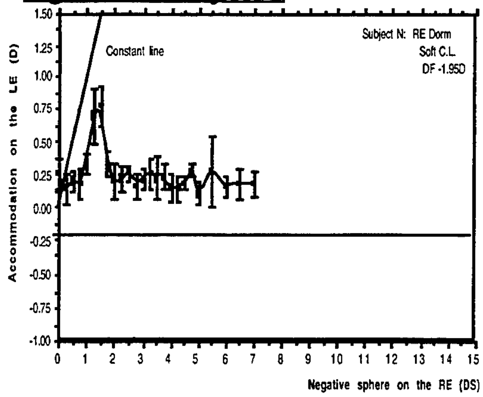


Figure 5.5: Subject RS

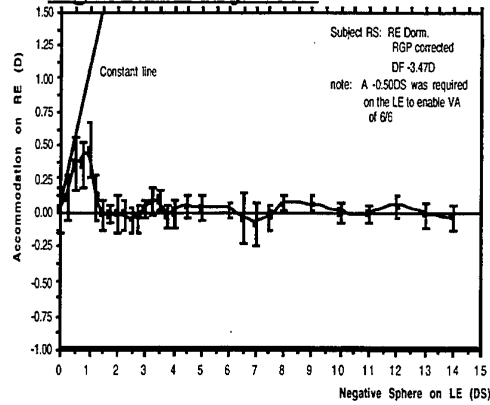


Figure 5.6: Subject AW

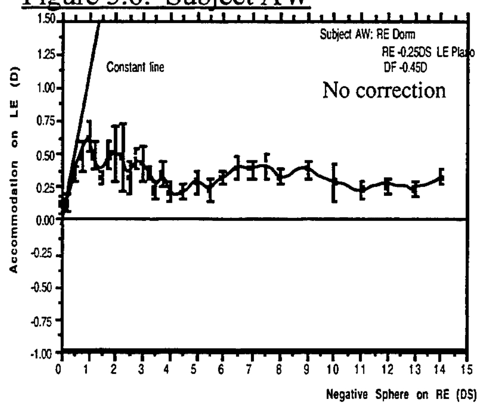


Figure 5.7: Subject SB

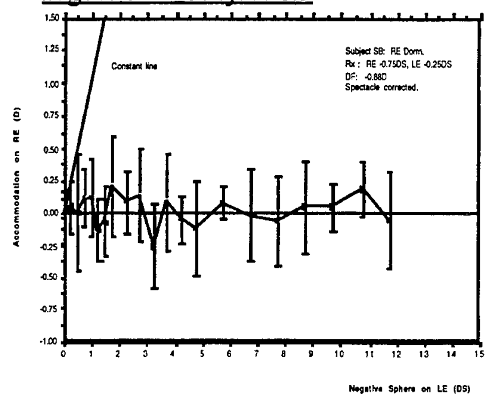


Figure 5.8: Subject S

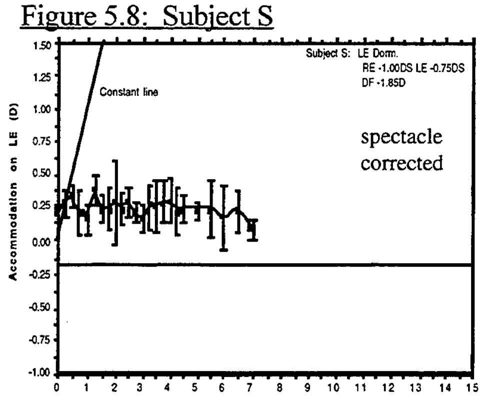


Figure 5.9: Subject AD

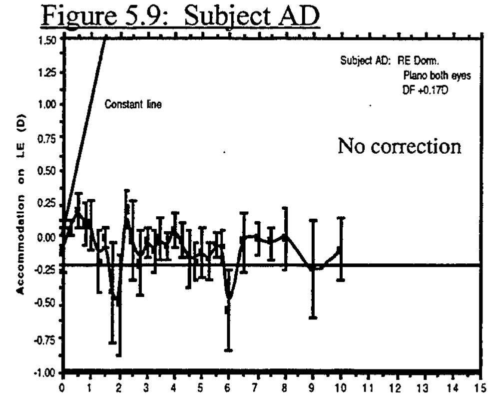


Figure 5.4 to 5.9: The stimulus/response curves of the 6 subjects. The stimulus is the negative sphere which we placed in front of the "with lens" eye (left eye for subject RS and SB). The response is the accommodation of the "no lens" eye (right eye for subject RS and SB) measured by the auto-refractor. The "constant" lines indicate a situation where stimulation = response, the horizontal lines indicate a situation where there is no response despite stimulation.

5.2.4 Discussion

As negative spheres were added to the "with lens" eye (which is dominant in 4 of the 6 subjects) various things might happen. The following possible simple models are proposed for the associated changes in the accommodation of the "no lens" eye.

i. Assuming that the accommodation of the two eyes is equal, accommodation might optimise vision for the "with lens" eye and the "no lens" eye would accommodate equally to track the "with lens" eye stimulus (following the "constant" lines of figures 5.4 to 5.9), resulting in a blurred image for the "no lens" eye.

ii. Since the "no lens" eye is not affected by the lens, it might drive the system and keep its accommodation constant. This would be expected if we assume that accommodation is fully "relaxed" for distance. The retinal image in the eye with the spherical lens would then be blurred

iii. Accommodation might try to equalise blur in the 2 eyes. (i.e. both right and left eye accommodation would equal half of the dioptric power of the lens)

iv. If the dark focus represents minimal accommodative "effort" (i.e. more effort is required to maintain distance vision) then accommodation might follow the "with lens" eye until the stimulus reaches the dark focus level. Beyond this, more effort would be required to keep the "with lens" eye in focus than the "no lens" eyes so that the system would prefer to rely on the "no lens" eye.

v. There might be "independent" accommodation of the 2 eyes, at least over a small range. This would mean that the "no lens" eye would stay constant while the "with lens" eye accommodated.

vi. At higher dioptric power, the negative lens would produce a minified retinal image thus causing refractive aniseikonia. The percentage of size difference in the retinal image is approximately 1.2% per dioptre of refractive anisometropia. (percentage size difference = $0.1d\Delta K$, where ΔK is the anisometropia in terms of ocular refraction, d = vertex distance which is assumed to be 12 mm). As a rule, a size difference of 5% or more will make fusion difficult. Suppression would result and binocular vision would break down. (A 5% size difference in the retinal image would correspond to about 4D lens power). Thus at -4.00DS, it is expected that

the suppressed eye would not response to the negative lens by accommodation, and in return the seeing eye's accommodation would not be affected.

Figure 5.10 shows schematically the results expected with the 6 possible models when negative spheres are added to one eye.

We can now compare the results shown in figures 5.4 to 5.9 with these model predictions.

It can be noted first that no subject showed changes of accommodation greater than 0.75D in the "no lens" eye and that any change was confined to cases where the magnitude of the negative lens power was less than -2.00D or -3.00D.

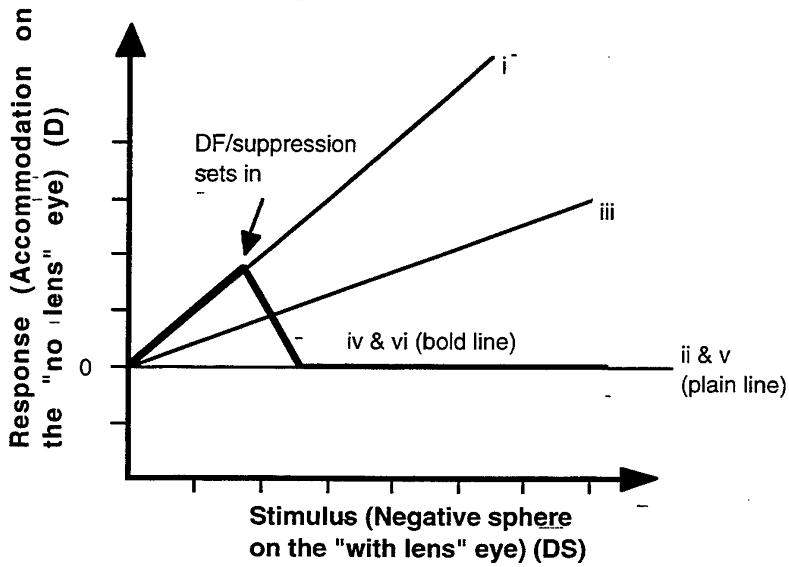


Figure 5.10: Schematic representation of the 6 possible models. ***(i)*** *Accommodation optimises vision for the eye with negative sphere and the other eye accommodates to track the fixation target.* ***(ii)*** *The eye without the negative sphere drives the system and keeps its accommodation constant. This would be likely if we assume that accommodation is fully "relaxed" for distance.* ***(iii)*** *Accommodation tries to equalise blur in the 2 eyes.* ***(iv)*** *Accommodation follows the eye which is stimulated with negative sphere until the stimulus reaches the dark focus (DF) level.* ***(v)*** *"Independent" accommodation of the 2 eyes, at least over a small range.* ***(vi).*** *Suppression occurs in the eye stimulated with negative lens and causes the breakdown of binocular vision. The unsuppressed eye takes over to drive the system and accommodation is kept constant. (note that the dioptric power of the negative sphere which causes suppression to occur and the dioptric power of the negative sphere to stimulate the eye to reach the DF may not be the same as indicated in the bold line graph.*

1. Model (i) does not occur except perhaps over first diopter or so. Even at this low stimulation, the fellow eye shows a lag in response (i.e. response < stimulation)

2. Model (ii) almost occurs for subject SB, S and AD. (note: Dark focus value for subject AD is effectively zero).

3. No evidence of model (iii).

4. Model (iv) might be true in some cases (e.g. subject AW) and conceivably in subject N and RS if their dark focus values were exaggerated. In general, however, it seems unlikely that this model is valid.

5. Since some "no lens" eye change occurs in the 3 subjects, model (v) cannot be completely true.

6. Assuming that when the range of negative spheres placed in front of the "with lens" eye, caused "with lens" eye to accommodate according to the dioptric power of the negative lens, there is no evidence for model (vi).

The most interesting finding is that weaker stimulation of accommodation in the "with lens" eye caused a small but ignificant increase in accommodation (though the increase is not equal to the stimulation) on the "no lens" eye for some subjects. (Refer to Appendix 5.2 which shows the results of pair 2 tails t-test to determine if there is any difference in accommodation of one eye when the other eye is stimulated). This behaviour is particular evident in subjects N, RS and AW. Subject AW showed significant increase in accommodation even when the other eye was stimulated to accommodate by 14D. However, the greatest amount of increase was at the lower range of stimulation.

The Increase in accommodation when the fellow eye was stimulated was always small. That means there was always a lag in response with respect to stimulation. The highest significant increase of 0.50D in accommodation was for subject AW when a -1.00DS was placed on one eye. Usually the increase in accommodation was in the range of 0.10D to 0.20D.

5.2.5 Conclusion

For 3 of the subjects there were a small unilateral shifts, suggesting that accommodation started by optimising the image from the "with lens" eye (left eye for subject RS). It appeared, however that the selected focus soon moved to the "no lens" eye (even though the "with lens" eye had not yet reached the dark focus value).

This study shows the significance of binocular equalisation in an optometric refraction because usually the degree of inequality between the 2 eyes is small, usually not more than 0.50DS. (i.e. smaller under-plused or over-minused in one eye stimulates more accommodation in its fellow eye than bigger under-plused or over-minused).

The major weakness in this experiment is that only the accommodation of the "no lens" eye was measured. We do not know how the "with lens" eye responded to the negative spheres, even though the subjects could still see the distance fixation target. Thus we cannot comment on whether aniso-accommodation occurred. Several authors in the past used lenses to stimulate accommodation (Leibowitz and Moore, 1966; Stoddard and Morgan, 1942) However, higher strength of negative spheres may not stimulate accommodation in the "with lens" eye, due to suppression, though the subjects can still see the distant target with their "no lens" eye. Thus a suppressed eye will not accommodate accordingly to the amount of negative sphere placed in front of it.

To find out more about the "with lens" eye response, the experiment was repeated on 3 subjects (subject N, RS and SB). This time, accommodation of both eyes was measured.

5.2.6. Experiment to determine how both eyes respond if one eye is stimulated with negative spheres.

The accommodation of both eyes when the subject viewed a distant (6m) 6/6 equivalent letter on a LogMar chart was measured with the Canon R1 auto-refractor. The accommodation of the "with lens" eye can be calculated from the auto-refractor readings using the following equation:

$$A = -(Fs + R) / [1-d(Fs + R)]$$

where A = Accommodation (D)

Fs = Back vertex power of negative sphere (D)

d = Vertex distance (m)

R = Reading obtained from the auto-refractor.

See Appendix 5.3 for the derivation of this formula.

For this equation to work, the "with lens" eye must be emmetropic or fully corrected.

Note that the accommodation in the two eyes had to be measured sequentially rather than simultaneously, but this should not matter in an essentially "steady state" experiment.

5.2.6.1. Stimulus/Response Models

There are 6 possible ways in which the "with lens" eye can respond. (Refer to figure 5.11)

i. The response equals the stimulus. This is the assumption we made in our previous experiment and is represented by (I) in the graph.

ii. Amount of response is less than the stimulus. Represented by (II) in the graph.

iii. The response exceeds the stimulus. Represented by (III) in the graph.

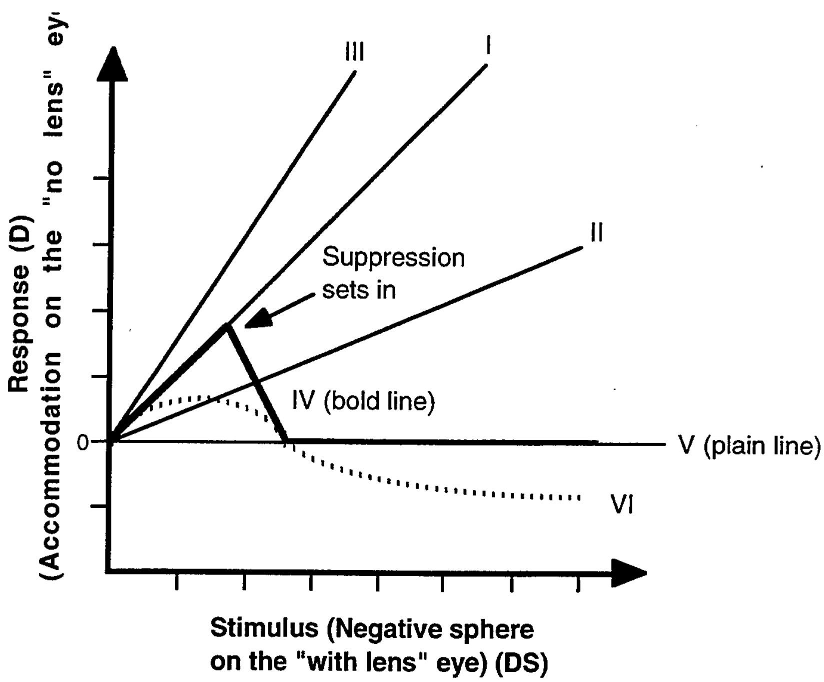


Figure 5.11: Stimulus/response curves of 6 possible models. ***(I)*** *Stimulus = Response.* ***(II)*** *Stimulus < Response.* ***(III)*** *Stimulus > Response.* ***(IV)*** *Suppression sets in to nullify the effect of stimulus (represented by the bold line).* ***(V)*** *Response = 0 at any amount of stimulus.* ***(VI)*** *Response > 0 at small amount of stimulus but Response < 0 at higher amount of stimulus. (represented by the dotted line).*

iv. The response increases with small amounts of stimulus but higher stimuli fail to elicit any response due to suppression. The "no lens" eye then controls the accommodation. Represented by (IV) in the graph.

v. No response is elicited by any amount of stimulus. Represented by (V) in the graph. In this case the accommodation is presumably controlled by the "no lens" eye.

vi. Higher stimuli reduce the response to a level lower than in a stimulus free situation. This might due to the fogging effect of high negative sphere. Represented by (VI) in the graph.

5.2.6.2. Subjects

The 3 subjects, N, RS and SB, who took part in this experiment had also taken part in the previous study. Note that N and RS showed some accommodation changes in the unstimulated eye in the earlier experiment, whereas SB did not

(Figure 5.4, 5.5 and 5.7) As in the previous study, the right eye of subject N and the left eye of subject RS and SB were stimulated with negative spheres

5.2.6.3. Results

The results obtained for the subjects are shown in figures 5.12, 5.13 and 5.14.

5.2.6.3.1 Subject N's result

Figure 5.12a Figure 5.12b

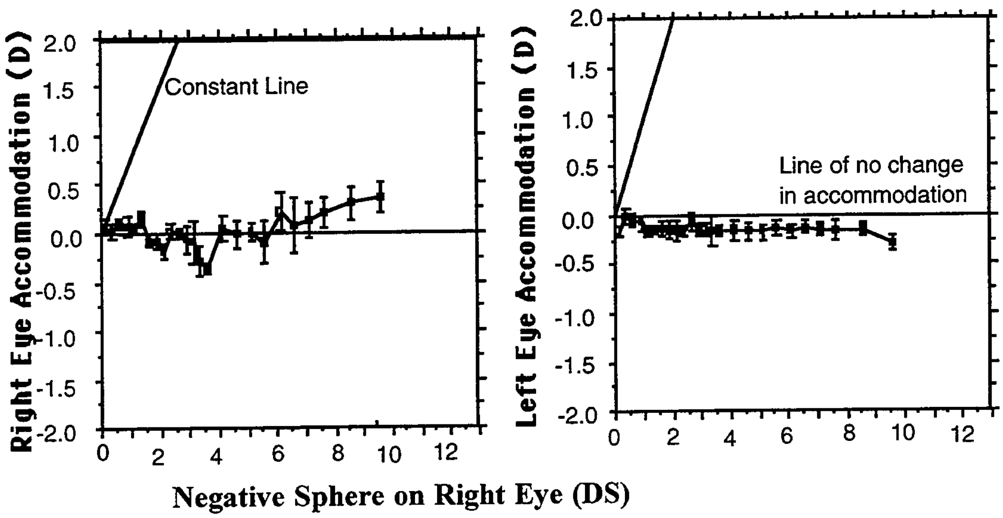


Figure 5.12c

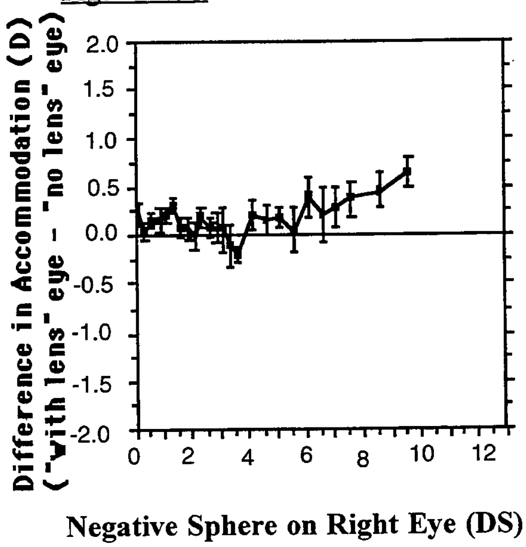


Figure 5.12a: Subject N 's right eye accommodation when her right eye was stimulated with negative spheres. Figure 5.12b: Subject N's left eye accommodation when her right eye was stimulated with negative spheres. Figure 5.12c: Difference in the accommodative response of the two eyes. (RE accommodative response - LE

accommodative response) The Y error bars = $\sqrt{s_1^2+s_2^2}$ *where s is the standard deviation. The constant line and line of no change in accommodation correspond to model (I) and model (V) in figure 5.11 respectively.*

From figure 5.12a, it was observed that for subject N, negative spheres on the right eye generally failed to stimulate the right eye to accommodate accordingly to the negative sphere dioptric strength. However the eye did apparently show a very slight increase in accommodation when it was stimulated with small negative spheres (up to -2.00DS) and large negative spheres (-6.00DS to -10.00DS). This increase in response was very small when compare to the amount of stimulation and may be a measurement artefact associated with the problem of using an autorefractor to estimate accommodation through negative lenses.

The probable problems are that with very high spheres, the auto-refractor cannot always measured accurately the state of accommodation Such high negative spheres produce a minified image on the display screens where measurements are made.and need to be tilted slightly on the trial frame in order to obtain some measurements, due to reflections from the lens surfaces. This tilting may affect the accuracy of the auto-refractor by introducing some cylinder power. Additionally quite small errors in the vertex distance d may generate significant errors in the estimates of accommodation.

Figure 5.12b shows the accommodative response of the left eye when the right eye was stimulated. The graph shows that the response was fairly constant (slightly less than 0.00D but greater than -0.25D) at all levels of right eye stimulation. (Similar to model (ii) in our previous experiment). The standard deviations were generally smaller than those at figure 5.12a (refer to the Y-error bars) Note that the result differs from that shown in figure 5.4 in the previous experiment.

Figure 5.12c shows the difference in the accommodation of the eyes. If appropriate systematic aniso-accommodation occurred, the difference would increase linearly with the power of the spectacle lens. Any such effect, occurring at low levels of lens stimulation would appear to be ≤ 0.25D.

5.2.6.3.2 Subject RS's result

From figure 5.13a, it was observed that for subject RS, negative spheres on the left eye also failed to stimulate the left eye to accommodate accordingly to the negative sphere dioptric strength. As with subject N, the stimulated " with lens" eye did show a slight trend of an increase in accommodation when it was stimulated with small negative spheres (up to -1.50DS). Such increase in response (~ 0.1D) was also very small when compared to the amount of stimulation.

Figure 5.13a

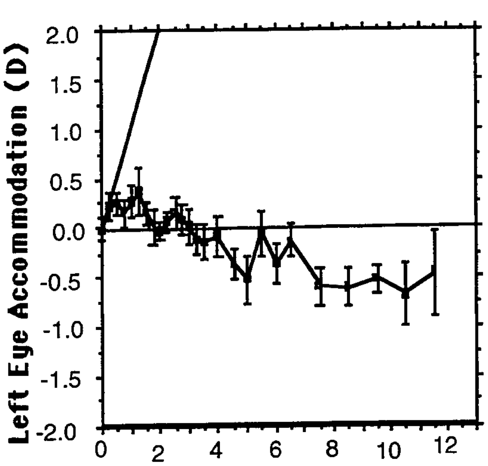
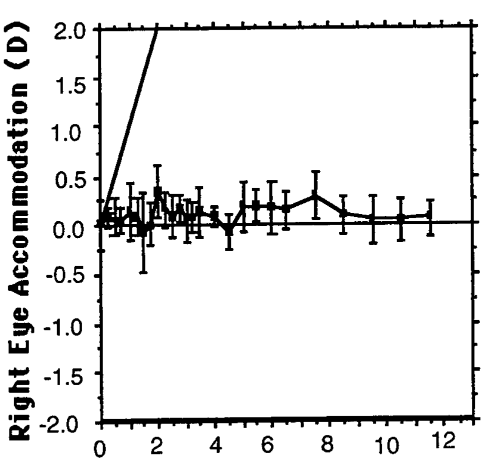
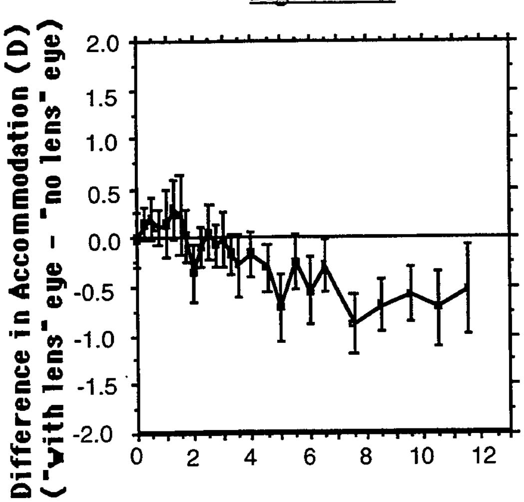


Figure 5.13b



Negative Sphere on left eye (DS)

Figure 5.13c



Negative Sphere on left eye (DS)

Figure 5.13a: Subject RS left eye accommodation when her left eye was stimulated with negative spheres. Figure 5.13b: Subject RS's right eye accommodation when her left eye was stimulated with negative spheres. Figure 5.13c: Difference in the

accommodative response of the two eyes. (LE accommodative response -RE accommodative response) The Y error bars = $\sqrt{s_1^2+s_2^2}$ *where s is the standard deviation.*

At greater amount of stimulation, instead of eliciting greater amount of accommodative response, the "with lens" eye showed a small "reduction" in accommodation of about 0.75D. However, we were not convinced of such "reduction" so we repeated the experiment and the same trend of response was recorded. (not shown in this thesis). It is again likely that this is an artefact associated with the difficulty of measuring accommodation behind high-powered lenses.

Figure 5.13b shows the accommodative response of the right "no lens" eye when the left "with lens" eye was stimulated. As with subject N, subject RS's right eye response was fairly constant (slightly more than 0.00D but lesser than +0.25D) at all levels of stimulation of the left eye. (Similar to model (ii) in our previous experiment)

Figure 5.13c shows the difference in accommodative response of the eyes. Remembering that we expect systematic aniso-accommodation to produce a gradually increasing difference, it is clear that any such effect is small (≤ 0.25D) The unstimulated eye's accommodation was less variable throughout the range of stimulation, while the stimulated eye's accommodation was more variable (an initial increase and follow by reduction).

5.2.6.3.4. Subject SB

Subject SB's response was quite similar to Subject RS. The "with lens" eye failed to accommodate accordingly to the amount of negative sphere stimulation. As the strength of negative sphere increases, the estimated accommodative response reduces. (figure 5.14a) Again, it is possible that this trend is an artefact of the measurement method, although there is no doubt about the failure of the eye to accommodate to overcome the negative sphere.

Considering the difference in the accommodation of the eyes (figure 5.14c) the autorefractor showed a slight refractive imbalance when the added lens power was zero. As the lens power increased there was no evidence of any appropriate aniso-accommodation.

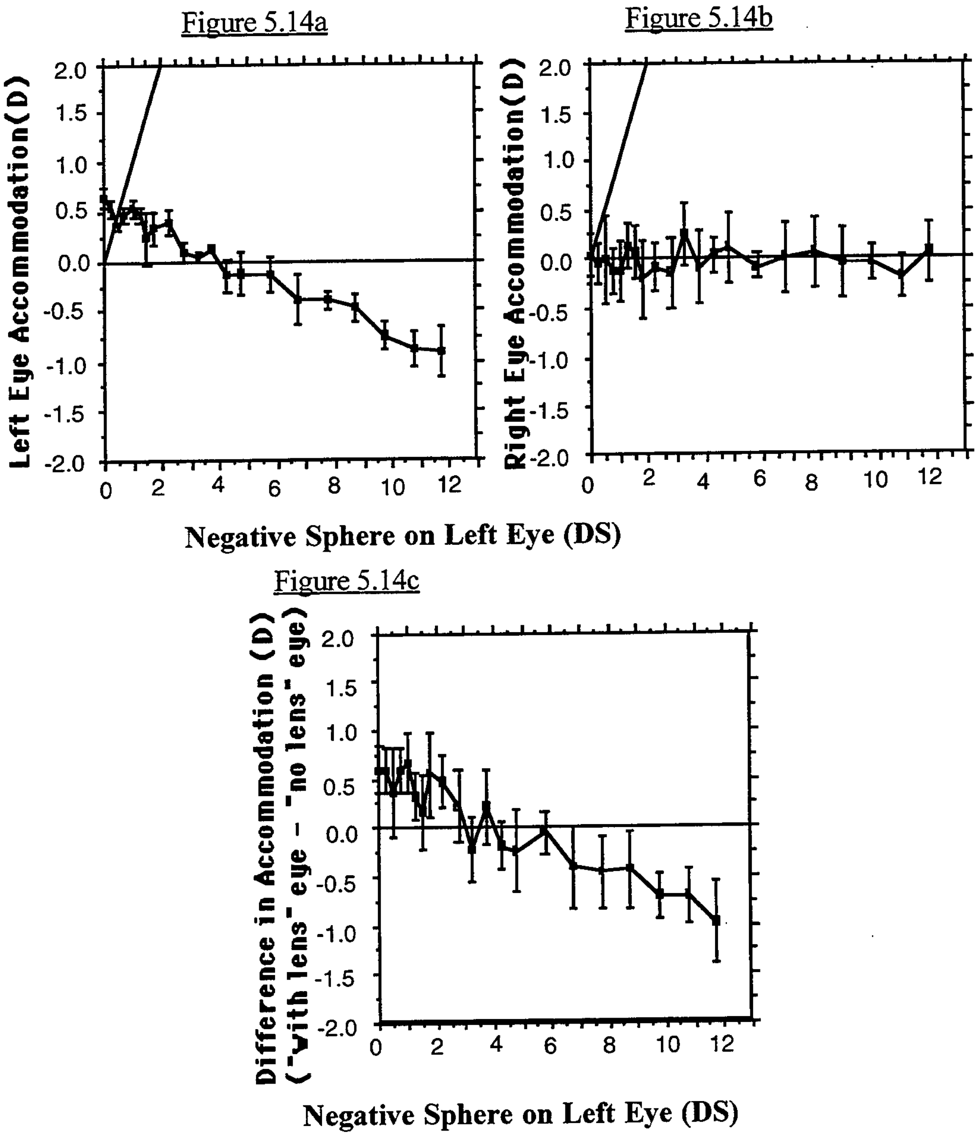


Figure 5.14a: Subject SB left eye accommodation when his left eye was stimulated with negative spheres. Figure 5.14b: Subject SB right eye accommodation when his left eye was stimulated with negative spheres. Figure 5.14c: Difference in the accommodative responses of the two eyes. (LE accommodative response -RE accommodative response)

5.2.6.3.4. Repeatability

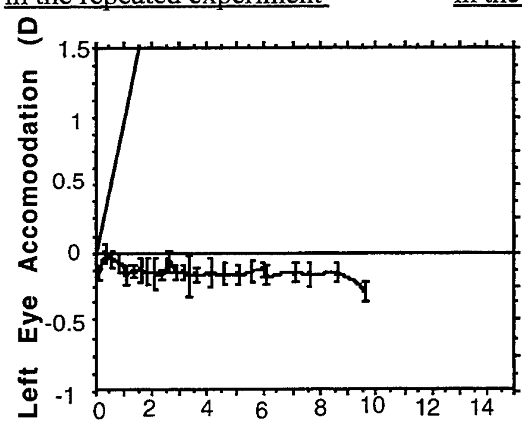
Figures 5.15 and 5.16 compare the accommodative responses of the unstimulated eyes of the 2 subjects on 2 different occasions under the same experiment set-up. The repeat experiment failed to reproduce exactly the

same trend of accommodative response in the earlier experiment, indicating the limited repeatability of results. However the differences between the two sets of results (a maximum of -0.25D) are modest in clinical terms.

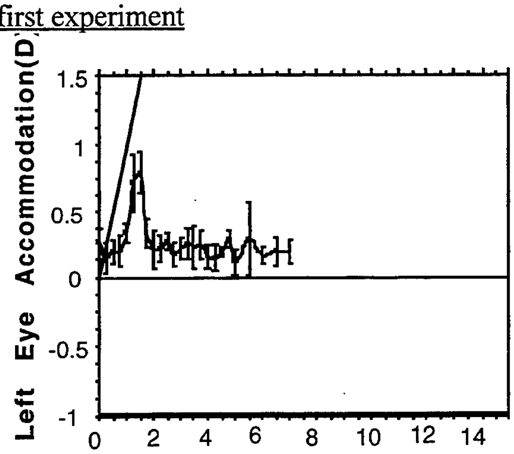
5.2.6.3.5. <u>Conclusion</u>

This experiment has shown that the assumption that during binocular observation when a negative sphere is placed in front of an eye, the lens will stimulate the eye to accommodate by the same dioptric power as the negative sphere, provided the subject still sees the distance fixation target is not justified.

<u>Figure 5.15a:Left eye's response in the repeated experiment</u>



<u>Figure 5.15b:Left eye's response in the first experiment</u>



Negative Sphere on the right eye (DS)

Figure 5.15a and 5.15b: Comparing Subject N "no lens" left eye's response under 2 different occasions but under the same experiment condition

Figure 5.16a:Right eye's response in the repeated experiment

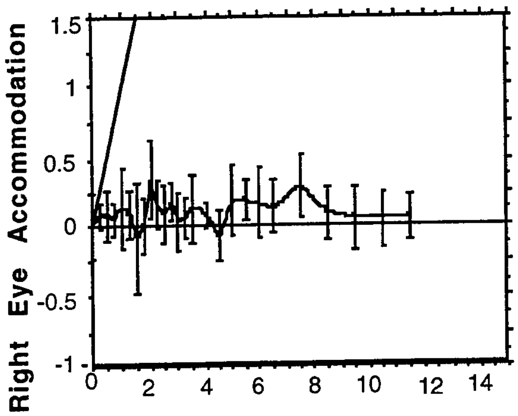


Figure 5.16b:Right eye's response in the first experiment

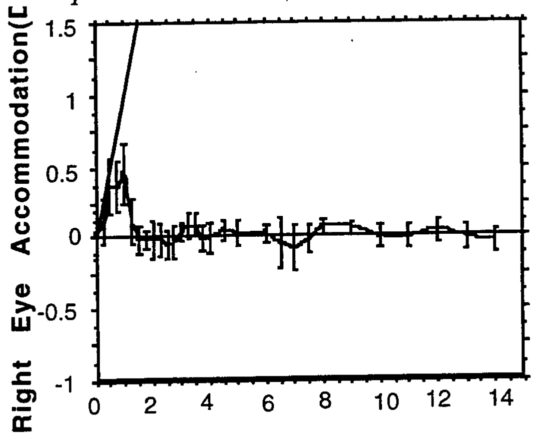


Figure 5.16a and 5.16b: Comparing Subject RS right eye's response under 2 different occasions but under the same experiment condition

In fact, from our results, there is an indication that the stimulus/response curve follow model (VI) (i.e. response > 0 at small amount of stimulus but response <0 at higher amount of stimulus). In the main, however, it appears that accommodation was probably controlled by the "no lens" eye. There was no strong evidence for the existence of appropriate, systematic aniso-accommodation which, if it occurred at all, had a magnitude ≤ 0.25D.

The accommodative responses of the unstimulated eye were not repeatable since different results were obtained in 2 different occasions under the same experiment set-up.

As already noted, a major weakness in this study was that the use of negative spectacle lenses introduced size differences between the two retinal images. In our next experiment in studying aniso-accommodation, negative spheres were no longer used to stimulate accommodation. Instead, fusible aniso-accommodative targets were presented to each eye. The 2 targets were Maltese crosses, each placed at a different vergence with respect to each eye

but both subtending the same visual angle.

5.3. Part II: Presentation of aniso-accommodative targets to the eyes

In this experiment, fusible aniso-accommodative targets were presented to each eye instead of using negative spheres to create targets with different vergences to each eye.

To prevent asymmetric convergence which can cause unequal accommodation (Rosenberg et al. 1953), the targets were arranged in such a way that fusion of the targets required the eyes to converge equally. A thin cross wire was placed at 37.5 cm (3.50D vergence) from the eyes to aid fusion of the two targets which were placed at 20 cm (5.00D vergence) and 50 cm (2.00D vergence) The distance of 37.5 cm was chosen because it lay exactly between the 2 aniso-accommodative targets in vergence distance. (2.00D + 5.00D) /2)

Accommodation of the 2 eyes was measured by the Canon R1 auto-refractor when the subjects fused the 2 aniso-accommodative targets.

The experiment was conducted in 2 parts. In the first part, accommodation was measured with the thin cross wire situated medially at 37.5 cm and the second part without the thin cross wire. Figure 5.17 gives a schematic diagram of the apparatus.

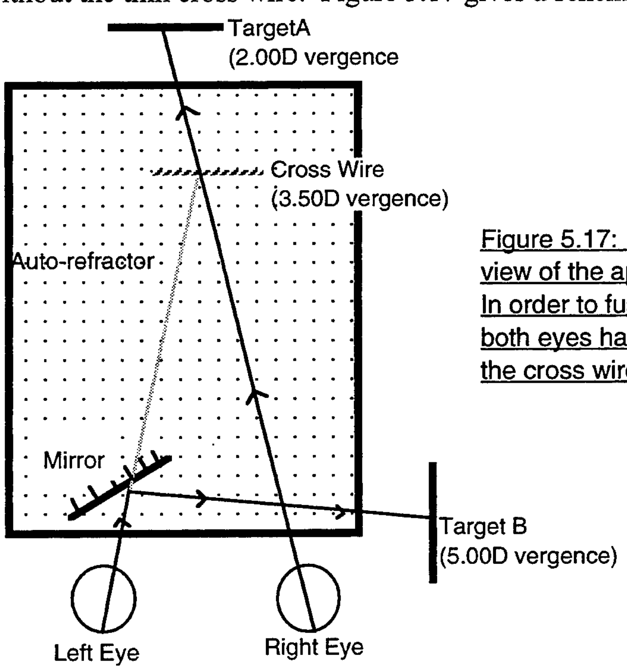


Figure 5.17: Schematic plane view of the apparatus set up. In order to fused the 2 targets, both eyes have to converge at the cross wire

5.3.1. Control Experiment

A control experiment was conducted to find out whether both eyes did accommodate equally when viewing a single target binocularly.
In this experiment, the subjects binocularly viewed a single, 3 degrees subtense, Maltese cross target situated at 20 cm from the eyes medially. Accommodation of the 2 eyes was measured.

The control experiment was repeated with a second cross target which also subtended 3 degrees but at the greater distance of 50 cm.

5.3.3. Targets

The two aniso-accommodative targets used are shown in figure 5.18. The targets were black Maltese crosses on a white background without one part of the vertical bar. Target A was placed at 50 cm and was seen only by the right eye. It did not have the lower vertical bar. Target B was placed at 20 cm and was seen only by the left eye. It did not have the upper vertical bar. Both targets subtended 3 degrees at the eyes.

Upon fusion of the two targets, the subject should see a complete Maltese cross (figure 5.18). He was asked to try to maintain fusion and clarity of the fused image while accommodation was measured on the two eyes.

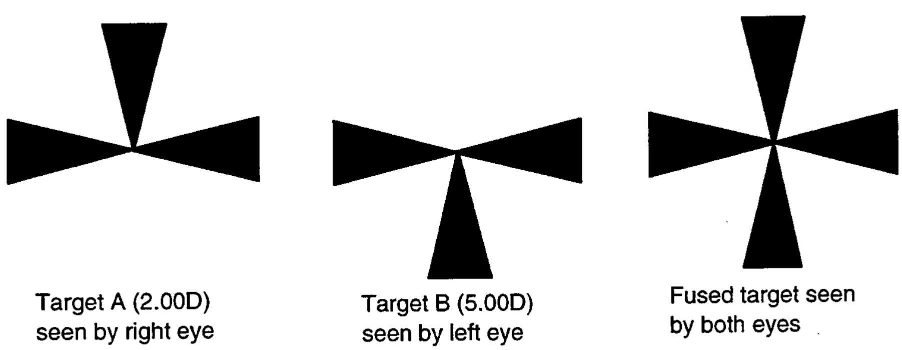


Figure 5.18: Targets A and B had visual angle of 3 degrees but had vergences of 2.00D and 5.00D respectively. The horizontal bar of both targets acted as a binocular lock to ease fusing of the targets. The fused target looked like a Maltese cross.

5.3.4. Models

Before the results of the experiment are discussed, 4 possible simple models might be proposed to describe the way in which the eyes might respond to the aniso-accommodative targets.

1. If the eyes responded to the aniso-accommodative targets by aniso-accommodation we would expect a graph which looked like figure 5.19a. The right eye would accommodate by 2.00D to see the target at 50 cm and at the same time, the left eye would accommodate by 5.00D to see the target at 20 cm.

2. Both eyes might accommodate to the dioptric middle point of the 2 aniso-accommodative targets. In our experiment, this point would be at 3.50D vergence. ({2.00D + 3.00D} /2) At this point, both targets would have equal retinal image clarity and supposedly aid fusion of the 2 targets. This model is represented in figure 5.19b. (note that the earlier experiments gave no evidence for this model).

3. Both eyes might accommodate to the farther target, which was at 50 cm. In this model, the right eye retinal image would be in focus while the left eye retinal image would be out of focus. See figure 5.19c. Such a response would involve the least accommodative effort.

4. Both eyes might accommodate to the nearer target which was at 20 cm. In this model, the left eye retinal image would be in focus while the right eye retinal image would be out of focus. See figure 5.19d. This type of response would involve the maximal accommodative effort.

A result close to model 1 would indicate that aniso-accommodation does exist in normal eyes. A result close to model 2, 3 and 4 would show that the eyes accommodate equally and indicate the preference of focal point during viewing of aniso-accommodative target.

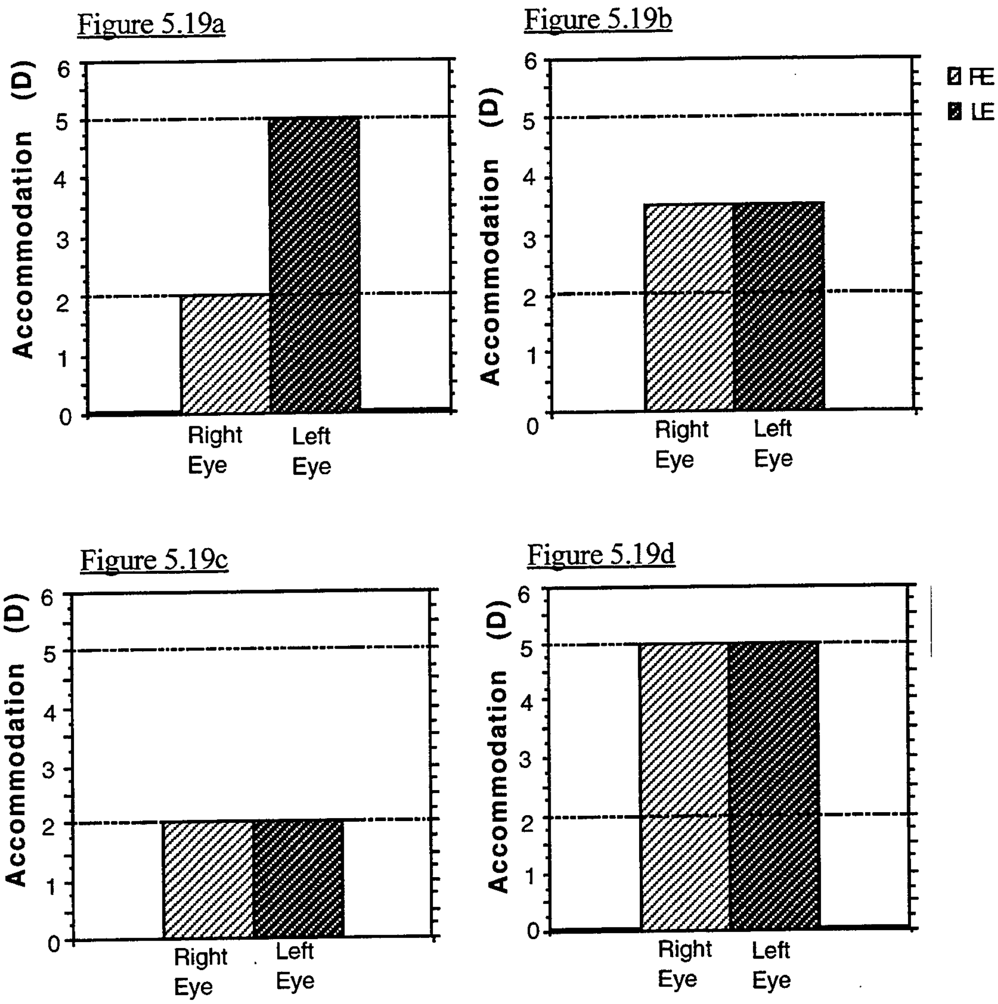


Figure 5.19. The right eye views the farther target at 50 cm and the left eye views the nearer target at 20 cm. 5.19a represents model 1 indicating aniso-accommodation of the eyes. 5.19b represents model 2 indicating the preference point of accommodation is between the dioptric distance of the 2 aniso-accommodative targets. 5.19c represents model 3 indicating the eyes preference to focus at the farther target. 5.19d represents model 4 indicating the eyes preference to focus at the nearer targets.

5.3.5. Subjects

6 young subjects (age 25.16 ± 2.32 years) participated in this experiment. Their refractive errors were fully corrected by either spectacle or contact lenses and they had an acuity of at least 6/6. All 6 subjects participated in parts 1, 2 and the control experiment.

5.3.6. Results

The results will be presented in the following 2 sections; with and without the cross wire at 37.5 cm.

5.3.6.1. With the cross wire at 37.5 cm

With the cross wire at 37.5 cm, we would expect the eyes to fuse the images more easily. At the same time, the cross wire might draw the eyes to accommodate at this distance.

Figure 5.20 shows the accommodative response of each subject when they viewed the aniso-accommodative targets.

A 2 tails paired t-test was used to test whether the accommodation means of the two eyes of each subject were significantly different. Of the 6 subjects, 4 showed a significant difference ($p < 0.05$) and 2 showed no significant difference ($p > 0.05$). The differences in accommodation in each subject range from 0.02D to 0.64D.

Of the 6 subjects, 4 subjects showed more accommodation in their right eyes which were looking at the farther target.

In 5 subjects, accommodation was in the region of 2.00D, indicating that the eyes tended to focus for the farther target. 1 subject (S) tend to focus at the region of 3.75D where the cross wire was situated.

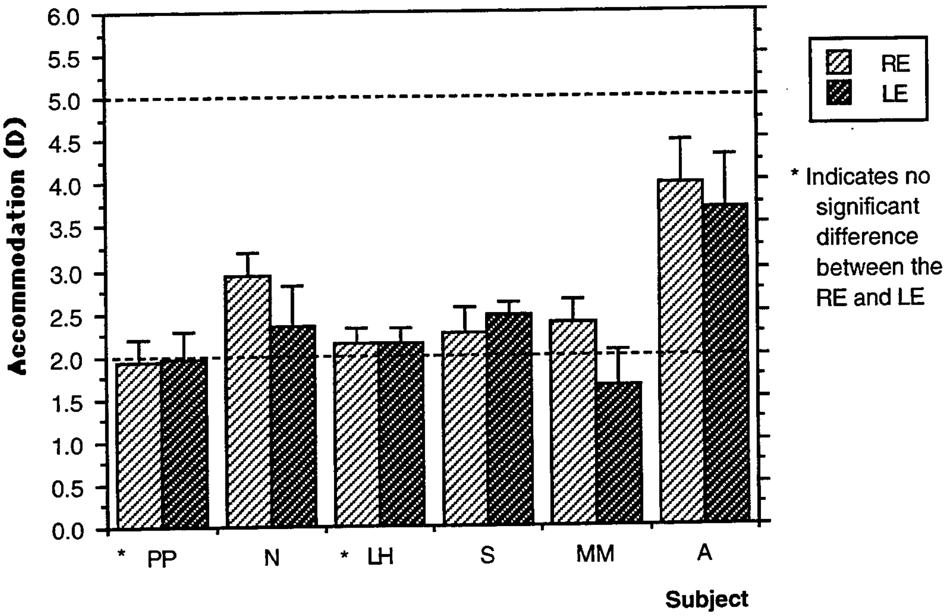


Figure 5.20: Comparing accommodation of both eyes when viewing aniso-accommodative targets (right eye viewed a target at -2.00D vergence, left eye viewed a target at -5.00D vergence ; both targets subtended 3 degrees to the eyes) A cross wire at -3.50D vergence was present to help the eyes to converge at this point.

Figure 5.21 indicates the composite accommodation mean of the 6 subjects. The composite right and left eye accommodation means were 2.75D and 2.54D respectively. The mean difference in accommodation of both eyes was 0.21D and a paired 2 tails t-test showed that these 2 composite means are significantly different. ($p < 0.0001$).

We know that the right eye was looking at the farther target of vergence 2.00D and the left eye was looking at the nearer target of vergence 5.00D. However it is noted that on the average, the right eye accommodated more than the left eye. Thus there is no evidence for appropriate aniso-accommodation.
It is also noted that the right eye showed an accommodative lead of 0.75D and the left eye showed an accommodative lag of 2.47D.

It could be argued that the right and left eye differences were caused by residual uncorrected refractive errors of the subjects instead of actual accommodation differences. However, since all the subjects' subjective refractive errors were fully corrected when they participated in the study, and it was assumed that subjective refractive errors were similar to objective refractive errors,. it was assumed that there was no objective refractive errors. The validity of the

assumption was explored more fully in the control experiments to be described in section 5.3.9.

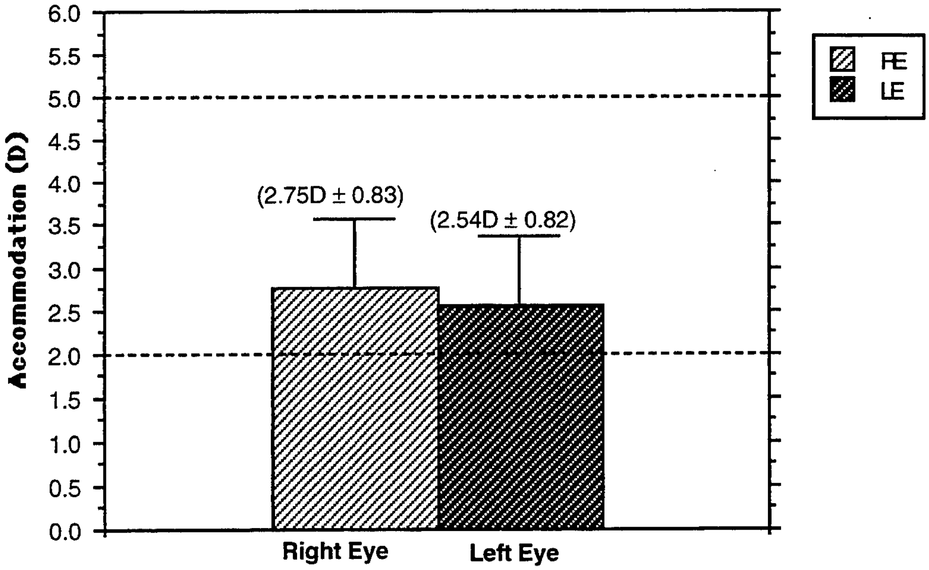


Figure 5.21: Composite accommodation mean of all the 6 subjects when viewing aniso-accommodative targets (cross wire present at 37.5 cm). 2 tailed paired t test showed a significant difference in accommodation of the 2 eyes with p <0.0001

5.3.6.2. <u>Without the Cross Wire at 37.5 cm</u>

Without the cross wire, we would expect that fusion of images would be slightly more difficult. However, no subjects reported that fusion was more difficult. Figure 5.22 shows the accommodative responses of each subject under the conditions.

A 2 tails paired t-test showed that 2 subjects (MM and A) had no significant difference in their right and left eye accommodation.

In 4 of the 6 subjects (PP, LH, S and MM) accommodation tended to shift towards the farther target of 2.00D vergence, and in 2 subjects (N and A) tended to shift towards the mid range of the 2 targets.

In 3 subjects (N, LH and MM) the right eye accommodated more than the left eye, even though the right eye viewed the farther target. Again, then, the result does not support the existence of appropriate aniso-accommodation.

Figure 5.23 gives the composite accommodation means of all the 6 subjects. A 2 tails paired t-test showed that the composite accommodation means between the right and left eye were not significantly different ($p = 0.68$). The composite right and left eye accommodation means were 2.75D and 2.73D respectively.

Thus on the average, the right eye had an accommodation lead of 0.75D and the left eye had an accommodation lag of 2.27D.

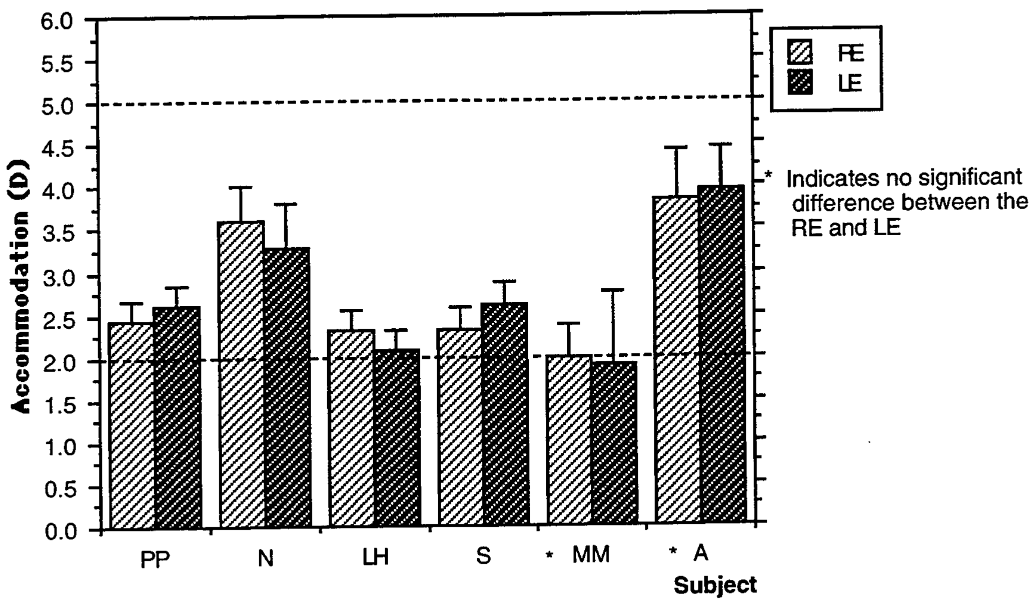


Figure 5.22: Comparing accommodation of both eyes when viewing aniso-accommodative targets (right eye viewed a target at -2.00D vergence, left eye viewed a target at -5.00D vergence; both targets subtended 3 degrees to the eyes). No cross wire present.

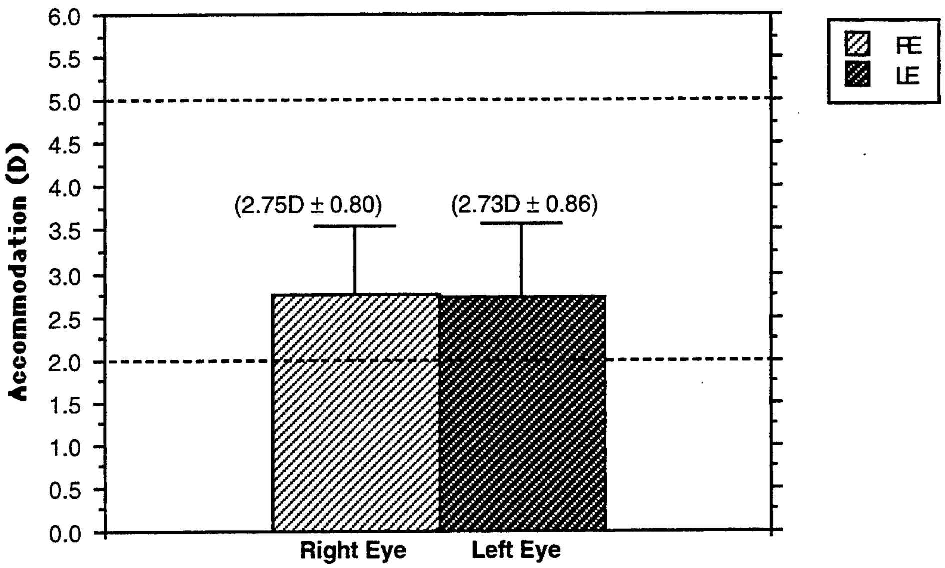


Figure 5.23: Composite accommodation mean of all the 6 subjects when viewing aniso-accommodative targets (No cross wire present at 37.5 cm). 2 tailed paired t test showed no significant difference in accommodation of the 2 eyes with p = 0.68

5.3.7. Control experiment

A control experiment was done to determine if there was any difference in accommodation when both eyes view the same target at 50 cm, and 20 cm which might be relevant to the search for systematic aniso-accommodation.

5.3.7.1. Viewing the -2.00D vergence target

Figure 5.24 shows the accommodative responses of each subjects when they viewed a single Maltese cross at 50 cm.

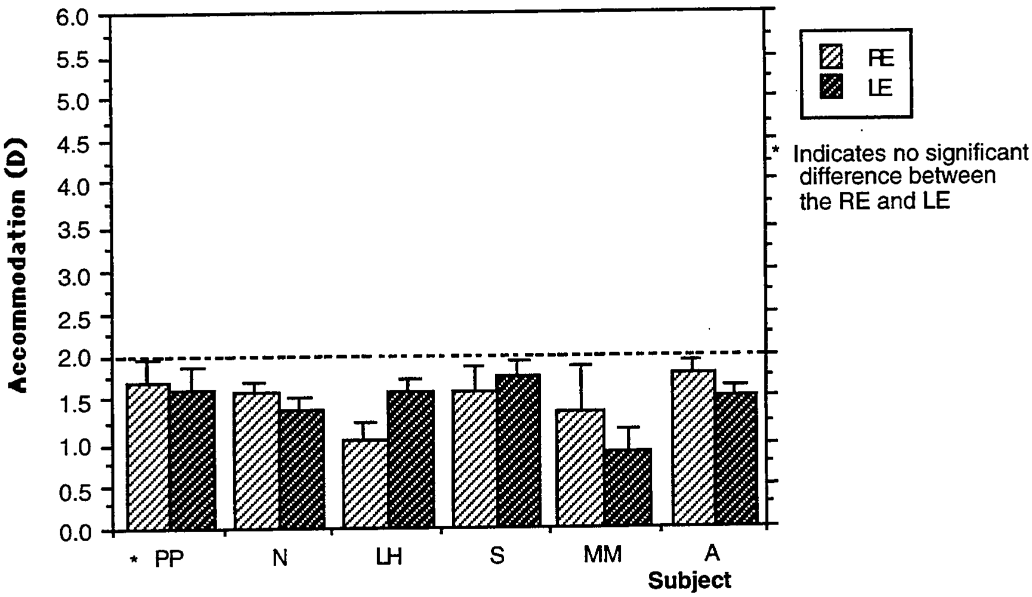


Figure 5.24: Control experiment. Both eyes viewed the same target at 50 cm (-2.00D vergence). The target was a Maltese Cross and subtended 3 degrees to the eyes.

All subject showed a lag in accommodation in both eyes. A 2 tails, paired t-test indicated that 1 subject (PP) showed no significant in the accommodation means of the right and left eye. The differences between the right and left eyes for the other subjects were all significant. The difference in accommodation between the right and left eye ranged from 0.10D to 0.55D.

Figure 5.25 shows the composite accommodation means of all the 6 subjects. A 2 tails, paired t-test showed that there is no significant difference between the composite accommodation means of the right and left eye ($p = 0.104$). The right and left eyes showed an accommodation lag of 0.51D and 0.57D respectively. Note that these levels are lower than those of the eye viewing the 2D target in the aniso-accommodation experiment, so that the presence of the 5D target and additional convergence demand in the latter experiment are affecting the accommodation of the eye which views the 2D target.

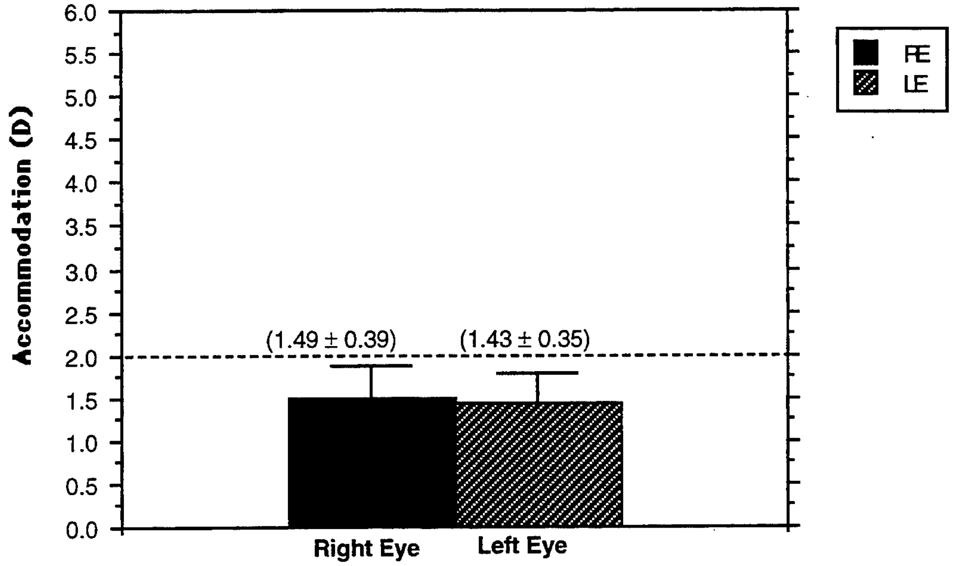


Figure 5.25: Composite accommodation mean for all the 6 subjects in the control experiment at 50 cm. A 2 tails, paired t-test indicated there was no significant difference in the composite accommodation mean of the right and left eye (p = 0.10)

5.3.7.2. Viewing the -5.00D vergence target

Figure 5.26 indicates each subject's right and left eye accommodative response when they viewed a single -5.00D vergence target binocularly.
All subjects showed an accommodative lag, especially subject LH (1.55D for right eye and 1.31D for left eye)

A 2 tails, paired t-test showed that 2 subjects (S and A) had no significant difference between the right and left eye accommodation means.

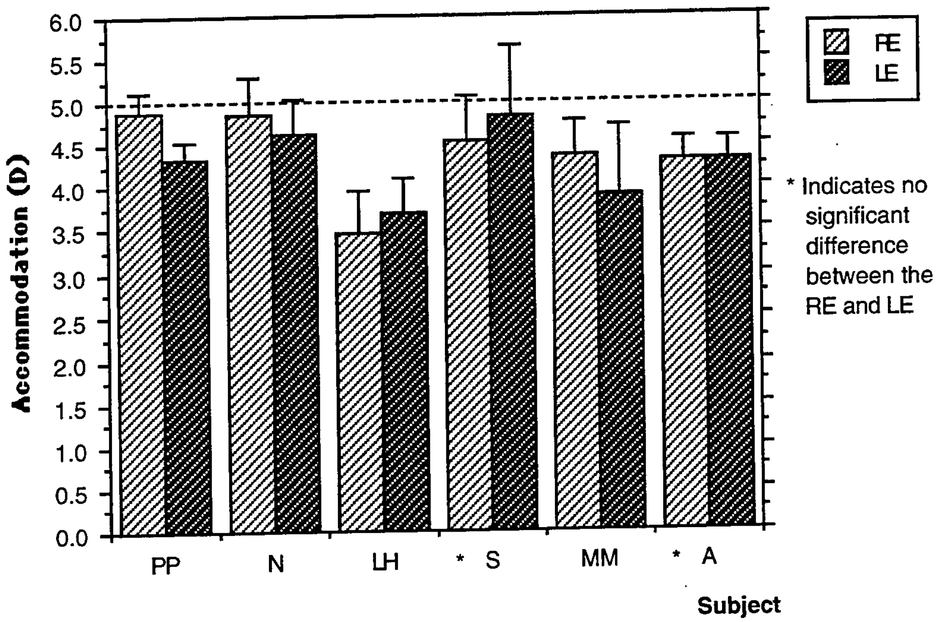


Figure 5.26: Control experiment: Both eyes viewed the same target at 20 cm (-5.00D vergence). The target was a Maltese Cross and subtended 3 degrees to the eyes.

Figure 5.27 indicates the composite accommodation means of all the 6 subjects, 4.36D for the right eye and 4.22D for the left eye. A 2 tails, paired t-test showed that these 2 means were significantly different. ($p= 0.02$) Thus the right eye accommodation mean was 0.13D more than the left eye.

Compared to the control experiment for accommodation stimulus at -2.00D, there was an increase in accommodation lag, 0.64D for the right eye and 0.78D for the left eye. This was in agreement with several authors (Morgan, 1944; Hennessy, 1975; Charman and Tucker, 1978) who note that the accommodative lag increases as the object distance is reduced. The accommodation to the 5D target in this binocular control study is much higher than that of the eye viewing the 5D target in the aniso-accommodative experiment.

In general these control experiments showed that the left and right eye accommodation responses were quite well balanced when both eyes viewed the same target. Thus the failure to observe systematic aniso-accommodation could not be attributed to any weakness in the accommodation of the "near" eyes.

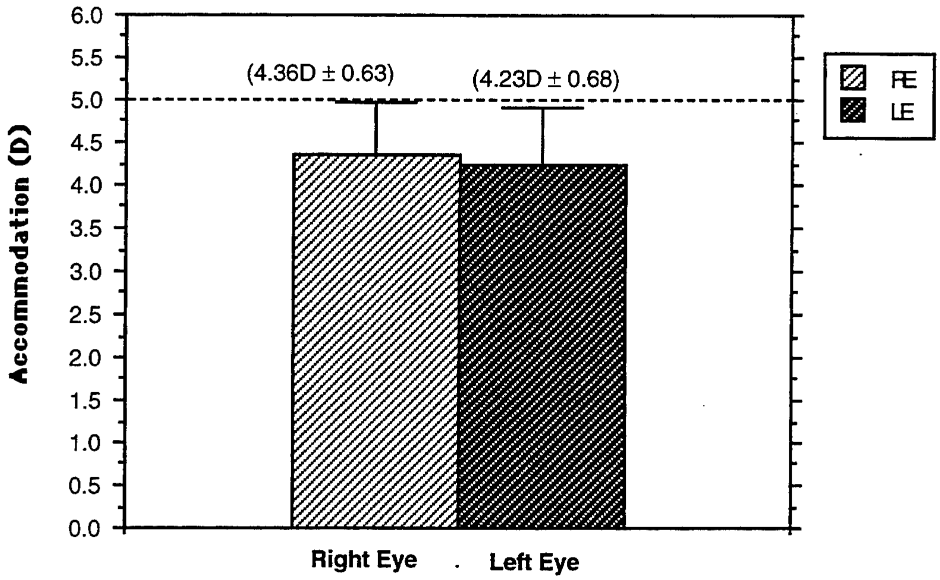


Figure 5.27: Composite accommodation mean for all the 6 subjects in the control experiment at 20 cm. A 2 tails, paired t test indicated there was a significant difference in the composite accommodation mean of the right and left eye. (p = 0.02)

5.3.8. Presentation of aniso-accommodative stimuli with only 0.5D difference in vergence.

It could be objected that the 3D difference in stimuli in the previous experiment was too large in comparison with natural aniso-accommodative stimuli, since the calculated difference in accommodation even for objects at 20 cm is less than 0.65D (refer to figure 5.3) for lateral fixation of targets.

To investigate this further, we repeated the experiment but with a 0.5D difference in stimuli. All experimental procedures and conditions were the same except that the right eye viewed a 2.0D vergence target, and the left eye viewed a 2.5D target.

Of the 6 subjects participating in this study, 5 subjects had participated in the previous experiment (Subject PP, N, LH, S and A). Subject SZ was a new subject who replaced subject MM who had left this country.

5.3.8.1 Results - With the cross wire at 2.25D vergence

Figure 5.28 shows the accommodative response of each subject when they viewed the aniso-accommodative targets with the cross wire at -2.25D vergence.

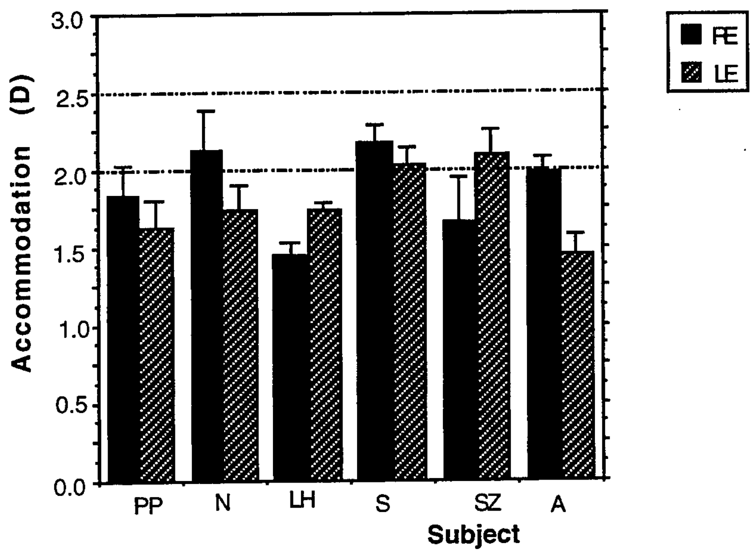


Figure 5.28: Comparing accommodation of both eyes when viewing aniso-accommodative targets (right eye viewed a target at -2.0D vergence, left eye viewed a target at -2.5D vergence; both targets subtended 3 degrees to the eyes. A cross wire at -2.25D was present)

A 2 tails, paired t-tests showed that all 6 subjects had a significant difference ($p < 0.05$) in accommodation of the right and left eyes.

Of the 6 subjects, 4 subjects showed more accommodation in their right eyes which were looking at the farther target. The greatest and smallest differences in accommodation were 0.53D for subject A and 0.15D for subject S respectively. 2 subjects, LH and SZ, showed that the left eyes accommodated more: 0.27D and 0.44D respectively. This was reasonable since the left target was situated nearer than the right target.

All 6 subjects' left eyes did not accommodate to 2.5D where the left eye stimulus was placed, thus showing a lag in accommodation in this eye.

The right eyes showed a lesser lag in accommodation. 4 subjects accommodated less than 2.0D, in which subject PP and A accommodated close to 2.0D. 2 subjects, N and S, showed a slight accommodative lead as their right eyes accommodated just over 2.0D.

Figure 5.29 shows the composite accommodation means of all the subjects right and left eyes response to the 0.5D difference in the aniso-accommodative targets.

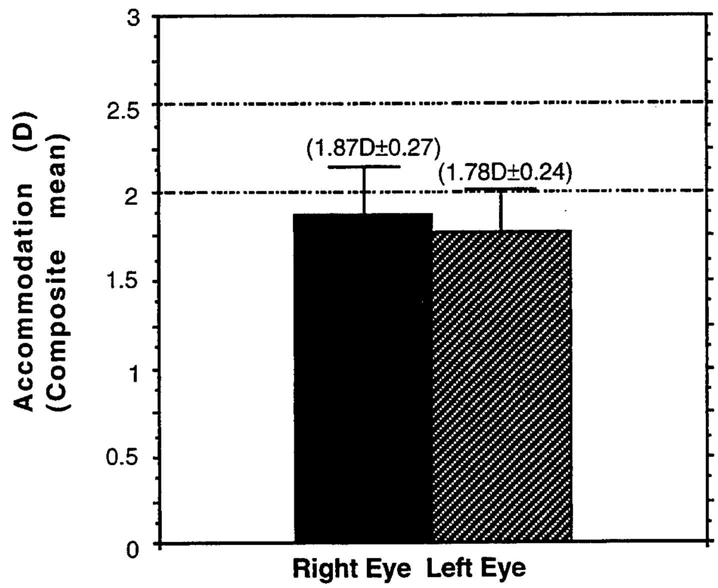


Figure 5.29: Composite accommodation mean of all the 6 subjects when viewing aniso-accommodative targets. (right eye viewed a target at -2.0D vergence, left eye viewed a target at -2.5D vergence; both targets subtended 3 degrees to the eyes) A cross wire at -2.25D was present) p = 0.58, indicates no significant difference between the right and left eye.

A paired, 2 tails t-test did not show any significant difference between the 2 composite means (p = 0.58). Both eyes accommodated close to 2.0D even though the left stimulus was situated at 2.5D and was 0.5D closer than the right stimulus. Thus there was no evidence for appropriate aniso-accommodation.

5.3.8.2. Results: without cross wire at -2.25D vergence

Figure 5.30 shows the accommodative response of each subject when they viewed the aniso-accommodative targets without the cross wire at -2.25D vergence.

Paired 2 tails t-tests showed that 2 subjects, LH and SZ, did not have any significant difference in their right and left eyes response to the aniso-accommodative targets.

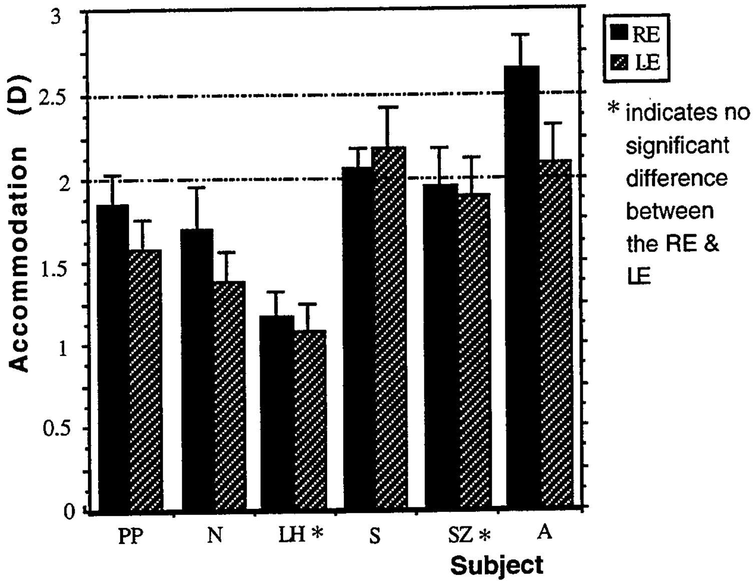


Figure 5.30: Comparing accommodation of both eyes when viewing aniso-accommodative targets (right eye viewed a target at -2.0D vergence, left eye viewed a target at -2.5D vergence; both targets subtended 3 degrees to the eyes.)

Of the 6 subjects, 5 subjects right eye accommodation means were greater than the left eye accommodation means though the right eye was viewing a farther target. The greatest difference in accommodation mean was 0.55D for subject A.

The absence of the cross wire seemed to have different effects on each subject. Subject LH and N showed more accommodation lag in both eyes than when the cross wire was present, subject A showed a lead in the right eye and less lag on the left eye and subject PP seemed not to be affected by the cross wire. (Compare figures 5.28 and 5.30)

Figure 5.31 shows the composite accommodation means of the 6 subjects.

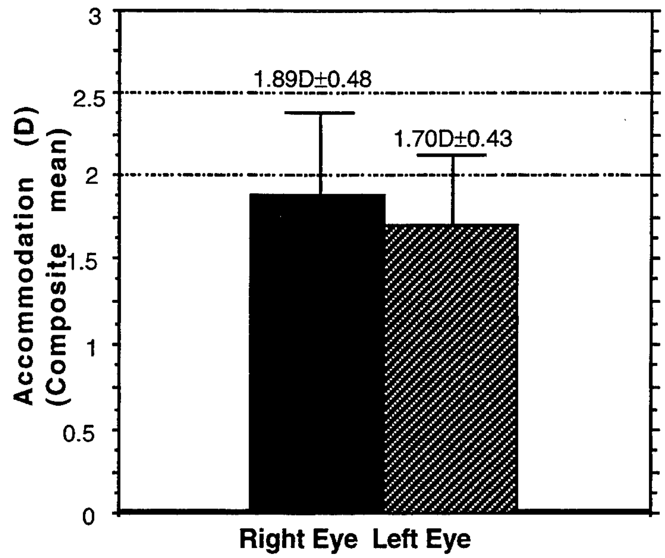


Figure 5.31: Composite accommodation mean of all the 6 subjects when viewing aniso-accommodative targets. (right eye viewed a target at -2.0D vergence, left eye viewed a target at -2.5D vergence; both targets subtended 3 degrees to the eyes) p = 0.10, indicates no significant difference between the right and left eye

A paired, 2 tails t-test showed there was no significant difference in the composite accommodation means of the right and left eye ($p = 0.10$), i.e. that there was no evidence for systematic aniso-accommodation. However, from figure 5.31, it was observed that both eyes composite means were below 2.0D and the left eye showed more accommodative lag than the right eye. This observation was also made in figure 5.29 when the cross wire was present.

5.3.9. Are Objective refractive errors similar to subjective refractive errors?

At the last paragraph of section 5.3.6.1 in this chapter, we assumed that subjective refractive errors of the subjects were similar to the objective refractive errors. Since all subjects were fully corrected by spectacle or contact lenses if they had any subjective refractive errors, the measurements we obtained from the auto-refractor were actually the accommodative responses rather than the objective refractive errors at the point of fixation.

To confirm this, we measured the response of the eyes when the subjects viewed a Snellen 6/6 letter at 6 m. The Canon R1 auto-refractor was used to measured the responses of both eyes when the subjects viewed binocularly at the Snellen 6/6

letter. The subjects were told to maintain clarity of the letter all of the time. Any subjective refractive errors were corrected by spectacle or contact lens. (i.e. on the duochrome test, the subjects saw the "red" just slightly clearer and a -0.50DS would make the "green" just slightly clearer. It is a normal practice for clinicians to slightly under-minus patients in a subjective routine at 6 m. The effects on vision of the small residual amount of uncorrected myopia can be overcome by the depth of focus of the eye when the patient views objects at infinity)

Results for individual subjects are shown in figure 5.32. It can be seen that the autorefractor gave results which showed, as expected, that most of the subjects eyes had slight "uncorrected myopia", in the region of 0.12D. This figure is so low that we can consider them to be emmetropic. Subject N was exceptional, being more under-corrected than the rest.

A paired, 2 tails t-test showed that only 1 subject (SZ) had no significant difference in the measurements obtained for the right and left eye. However the difference in the measurements in all of the subjects were very slight. The largest and smallest differences were 0.24D for subject PP and 0.02D for subject SZ respectively.

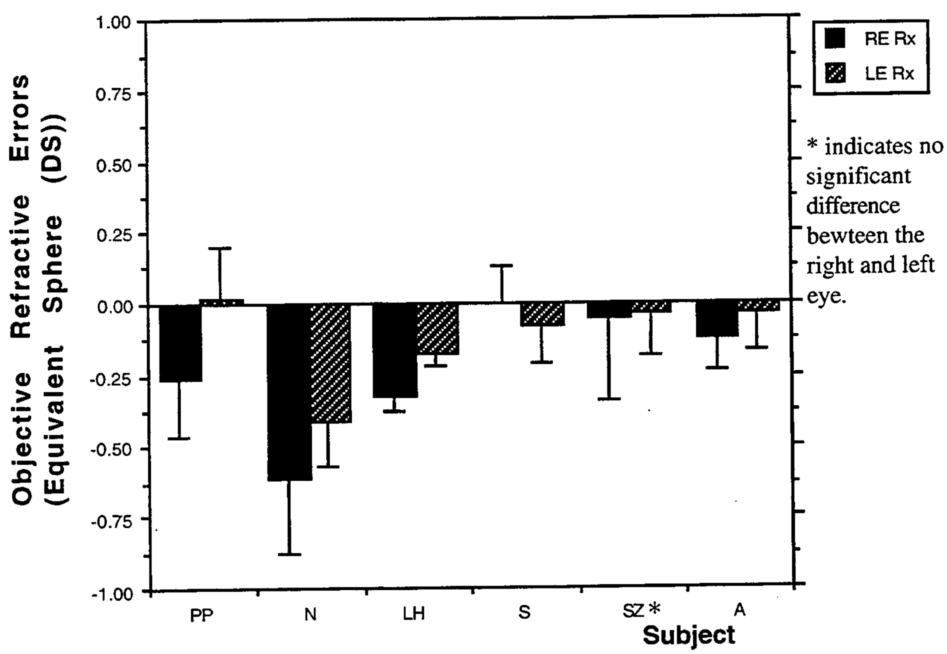


Figure 5.32: Objective refractive errors of the subjects. Measured by the Canon R1 autorefractor when the subjects viewed a 6/6 Snellen letter at 6m binocularly with full correction of subjective refractive errors.

Figure 5.33 shows the composite means of objective refractive errors of all the subjects. A paired, 2 tails t-test showed that the 2 composite means were not significantly different. The composite means were small, -0.23DS and -0.12D for the right and left eyes respectively.

Thus it can be concluded it was justifiable to assume that subjective refractive errors were similar to objective refractive errors, and that the responses obtained by the auto-refractor were actually the accommodative response.

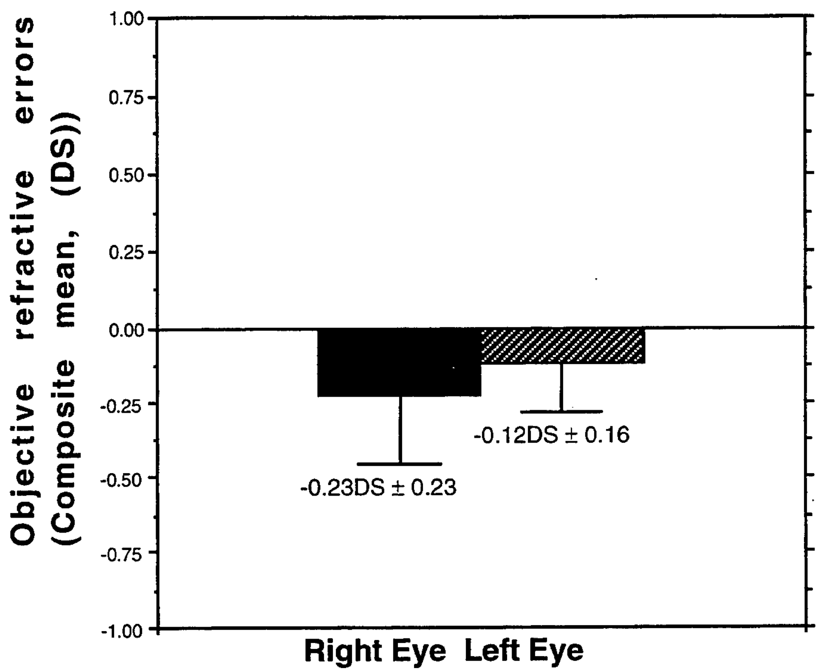


Figure 5.33: Composite mean of the objective refractive errors of the subjects. ($p > 0.05$, indicates no significant difference between the right and left eye).

5.3.10. Discussion

From the result of this experiment (see Table 5.1 for a summary of results) there is no indication that the eyes can accommodate differently and exactly on aniso-accommodative targets. In the experiment with 3D difference in the aniso-accommodative stimuli and where the cross wire was present, there was a slight, significant difference in accommodation between the 2 eyes. However, the difference was relatively small (0.21D) in comparison with the difference in vergence (5.00D - 2.00D = 3.00D) of the 2 targets. Moreover, such a difference cannot be ascribed to the viewing of aniso-accommodative target because the right eye was viewing a farther target but the accommodation mean was higher than the

left eye. In addition, the control experiment at 20 cm showed that the 2 eyes' accommodations could be significantly different (0.13D), even though both eyes were viewing the same target.

Table 5.1: Summary of results

3D Difference in Aniso-Accommodative Stimuli				
	With Cross Wire (D)	Without Cross Wire (D)	Control	
			20 cm	50 cm
Right Eye	2.75±0.83	2.75±0.80	4.36±0.39	1.49±0.39
Left Eye	2.54±0.82	2.73±0.84	4.22±0.68	1.43±0.35
Difference	0.21	0.02	0.13	0.06
p value	$p<0.001$	$p=0.68$	$p=0.02$	$p=0.10$

0.5D Difference in Aniso-Accommodative Stimuli			
	With Cross Wire (D)	Without Cross Wire (D)	Objective Refractive Errors (DS)
Right Eye	1.87±0.27	1.89±0.48	-0.23±0.23
Left Eye	1.78±0.24	1.70±0.43	-0.12±0.16
Difference	0.09	0.19	0.11
p value	$p=0.58$	$p=0.10$	$p=0.10$

Our results were similar to that of Calin et al (1996). Their subjects responded to the position of lower vergence when presented with aniso-accommodative stimuli.

When evaluating the small inter-ocular differences in accommodation that were recorded, several factors must be considered.

It is well known that few people can maintain absolutely steady accommodation on a near target: slow drifts normally occur, interspersed by "accommodation saccades" where clear vision is established. With the Canon instrument, accommodation was measured first for one eye and then for the other, so that any drift in mean levels would give rise to a apparent inter ocular difference, even if in fact the accommodation responses of the eyes were always identical.

It is also possible that there may be small differences in the accommodation efficacy of the eyes, due to small differences in the structures of the two ciliary

bodies, lenses, etc. Thus even if the innervation to the two eyes was identical, the resultant accommodation achieved might differ slightly. Such minor differences were found, e.g. by Ramsdale (1979, 1982).

The size of the natural pupil changes constantly though the luminance level stays the same. A slight increase in the sympathetic innervation (e.g. during exciting thoughts) will dilate the pupil and an increase in parasympathetic innervation (e.g. boredom, sleepiness) will constrict the pupil. Such changes in pupil size also change the depth of focus which in turn affects accommodation. An increase in depth of focus will result in a reduction in accommodative response and vice versa. It is probable that in experiments of the present type our subjects, after staring too long at the targets, occasionally felt bored and sleepy which resulted in constriction of the pupil (increase in parasympathetic innervation). Then suddenly they may have been "awakened" by being reminded to keep the targets in focus which resulted in dilation of the pupil.

Marran and Schor (1996), who found some evidence for aniso-accommodation, did not agree with this view. They concluded that aniso-accommodation is not the result of rapid monocular changes in accommodative state nor is it dependent on pupillary constriction. They did not state in the abstract of their paper how much aniso-accommodation the eye can manage, However, Marran (1995) found that the visual system can respond to anisometropic stimuli due to design flaws in HMDs, with aniso-accommodation of up to 1D

5.4. Implications for Optometry

In section 5.1, we mentioned possible implications of this aniso-accommodation study for optometric practice. These are now discussed .

Binocular equalisation (also known as binocular balancing) is followed by monocular refraction of the both eyes in a refraction routine. The purpose of this routine is to attempt to equalise the clarity of vision in both eyes since a different state of relaxation of accommodation might have prevailed during monocular refraction. If such difference in the state of relaxation of accommodation does occur, it is usually small. (0.07D to 0.28D for distant viewing, see section 3.3.2)

In section 5.2, we found that when one eye was stimulated with weak concave spheres (less than -3.00DS), the other eye (i.e. the "no lens" eye) occasionally

showed a significant increase in accommodation. However, such increase in accommodation was always small and never equal to the stimulation. The highest increase was 0.50D when the other eye was stimulated with a -1.00DS (subject AW). Thus this study shows the desirability of this binocular equalisation in a refraction routine to prevent the eyes to accommodating unnecessaryily

Since there is no evidence of systematic aniso-accommodation, and accommodation is controlled by the eyes viewing the farther target, it has the following implications for some young patients:

1. If one eye is myopic and the other eye is emmetropic or hypermetropic, accommodation in the myopic eye will control accommodation in near work. The emmetropic/hypermetropic eye will fail to accommodate to the near working distance even though the patient has sufficient amplitude of accommodation. Such response will also be expected in an early presbyope who has monovision due to contact lens correction (distance prescription for one eye and reading prescription for the other eye).

2. If one eye is hypermetropic and the other eye is emmetropic, the emmetropic eye will control accommodation for distant and near viewing. Thus the hypermetropic eye will have a clear retinal image at all times, which may lead to the development of amblyopia in the young.

3. If one eye is hypermetropic and the other eye is myopic, the hypermetropic eye will control accommodation for distant viewing. The myopic eye will also accommodate by approximately the same amount as the hypermetropic eye, thus cause the retinal image in the myopic eye to be more blurred.

Inaccurate refraction in one eye (e.g. over-minused or under-plused) and accurate refraction in the other eye by the clinician will effectively render the young patient anisometropic and, as a result, the accommodation system will be affected as described above.

5.5. Conclusion

This study failed to find any evidence supporting the concept of systematic aniso-accommodation. In general, when the eyes were presented with unequal accommodative stimuli, accommodation was mainly controlled by the eye viewing the farther target, i.e. accommodation effort was minimised. A similar effect is seen in accommodation for astigmatic eyes, where accommodation usually brings the focal line which demands least effort onto the retina. (Freeman, 1975).

CHAPTER 6: THE EYE'S RESPONSE TO VIRTUAL REALITY IMAGES

Under normal viewing conditions, accommodation and convergence vary synkinetically, and are dependent on object distance. This synkinesis was initially described by the German physiologist, Mueller in 1826, (cited by Ciuffreda and Kenyon 1983). The first objective recordings of accommodative vergence were performed by Alpern and Ellen (1956) using electrooculography. They showed that the covered eye changed position with stimulus to accommodation, but that the viewing eye remained stationary. Subsequently, Semmlow and Venkiteswaran (1976) showed evidence for binocular accommodative vergence.

In some situations, as when viewing a virtual reality display or during a stereoscopic test (e.g. a random dot stereograms) this synkinetical relationship can be broken down.

In a virtual reality system, the eyes must remain focused on the fixed liquid crystal display (LCD) screens despite the presence of depth cues in the visual space which tend to drive convergence and accommodation away from the plane of the display. The screens are viewed through +36D compound lenses, with each LCD screen placed close to the focal point of its compound lens. The proximity effect associated with such close viewing distance may further disrupt the normal relationship between convergence and accommodation.

Similar effects occur with many tests for stereoscopic vision. In a stereoscopic test, half images must be presented to each eye separately and simultaneously. These half images, representing the two different retinal views of a three dimensional scene will evoke the perception of an image in depth. If the retinal images are to be properly in focus, the eyes must accommodate on the half images, but the perception of the 3-D image may disrupt this relationship.

In this chapter, an experiment is described in which the accommodation of the eyes is measured when subjects view 3-D percepts generated by 2-D stereo pairs (the TNO test and the Lang-Sterotest I).

The TNO test is an anaglyph (a 2-D image) consisting of a random-dot stereogram in which the half images have been superimposed and printed in roughly complementary colours. In order to ensure that each eye receives only one of the two images, the

pictures are viewed through red and green filters that transmit either one or the other of the printed colours.

The Lang-Stereotest I uses both random dots and cylinder gratings. The images to be viewed by the two eyes are seen through a system of fine, parallel, transparent, cylindrical strips. Beneath each cylinder there are two fine strips of pictures, arranged so that as viewed through the refracting cylindrical strips, one is seen by the right eye and the other is seen by the left eye. This test does not require the use of tinted or other glasses and accommodation can be measured with the auto-refractor with ease.

6.1 Method

The Lang-Stereotest I was used in the first part of the experiment. The test was held exactly at right angles (frontoparallel) at a distance of 40 cm in front of the subject. The subject placed his/her head on the auto-refractor (Canon R1) and was asked to look at the "Cat" which had a disparity of 1200 seconds of arc. Once the "Cat" with crossed disparity was seen, the subject was told to concentrate on the 3-D image and accommodation was measured on one of the eyes. Accommodation of the same eye was also measured when the subject viewed a 2-D "Cat" of the same size at the same distance and under the same room lighting condition. At least a dozen readings were taken for each viewing conditions in random order.

Since the Lang-Stereo test I cannot simulate uncrossed disparity image, the experiment was repeated with a TNO test. This time, the subject was asked to look at the "Butterfly" which also had a disparity of 1200 seconds of arc. Accommodation of the left eye was measured (the red filter of the red/green spectacle was on the left side) under 3 viewing conditions: "butterfly" with crossed disparity; "butterfly" with uncrossed disparity (i.e. with the test inverted); and without any disparity (i.e. the subject viewed the test without wearing the red/green spectacle.). The test was placed at 40 cm and the viewing conditions were presented in random order to the different subjects..

6.2. Subjects

10 subjects (age 22.4 ± 3.63 years old) were recruited for part I, and 9 subjects (age 22 ± 2.7 years old) were recruited for part II of the experiment. All subjects except 3 had TNO stereoacuities of at least 60 seconds of arc. Subject P and AS had stereoacuities of 240 seconds of arc and Subject RF had stereoacuity of 120 seconds of arc. Despite

their sub-normal stereopsis, these 3 subjects could still see comfortably the 1200 seconds of arc images: thus they were used in this study. However their results are excluded in the computation of the composite means. All subjects' refractive errors were fully corrected. Refer to Appendix 6.1 for their visual characteristics.

6.3. Results

Part I

The full results obtained by each subject during part I of the experiment are given in Appendix 6.2. Table 6.1 shows the summarised results for accommodation when the subjects viewed the crossed and zero disparity Lang-Stereotest images.

	Crossed Disparity Image			Zero Disparity Image			Diff. in
Subject	Sph.	Cyl	Eff. Sph.	Sph.	Cyl.	Eff. Sph.	Eff. Sph.
D	2.18	0.89	2.63	1.65	0.89	2.10	0.53
P	*1.81*	*0.45*	*2.04*	*1.51*	*0.53*	*1.78*	*0.26*
S	1.58	0.85	2.00	1.48	0.85	1.91	0.10
C	1.35	1.54	2.12	1.79	1.43	2.50	-0.38
R	1.76	0.34	1.93	1.51	0.43	1.73	0.20
H	1.76	0.82	2.17	1.38	0.98	1.87	0.30
SP	1.93	0.37	2.11	1.81	0.46	2.04	0.07
DB	1.66	1.12	2.22	1.75	0.93	2.22	0.00
M	1.49	0.94	1.96	1.38	1.34	2.05	-0.09
B	1.78	0.90	2.23	1.68	0.89	2.12	0.10
Mean	1.72	0.86	2.15	1.60	0.91	2.06	0.09

Table 6.1: Average accommodation of the left eye as measured by the auto-refractor when the subjects viewed the Lang-Stereo Test I (Cat with disparity of 1200 seconds of arc) and a 2-D image of a cat of the same size and at the same distance. Subject P's results are excluded in the computation of the mean because he has subnormal stereopsis.

It was observed that most subjects showed an increased in accommodation when viewing the crossed disparity image of the "Cat". Subject C was an exception who showed a significant decrease in accommodation of 0.38D.

Table 6.2 showing the p values of the paired, 1 tailed t-test for each subject under the 2 viewing conditions. In evaluating these and later results it must be borne in mind

that the expected differences in accommodation are quite small (about 0.1 D, see section 6.4 below) , that any optometer has limited relaibility, and that several factors may contribute to small systematic drifts in accommodation during experiments of this type.

Subject	p-value
D	<0.001
P	<0.001
S	*0.279
C	0.001
R	0.008
H	0.002
SP	0.015
DB	*0.493
M	0.044
B	0.008

*Table 6.2: Indicates the p values from the paired, 1 tailed t-test to determine if there was a difference in the mean accommodation when the subject viewed the crossed disparity image of the "Cat" and the zero disparity image of the "Cat" of the same size and distance. * indicates the 2 means are not significantly different*

Overall, there was a composite mean increase in accommodation of 0.09D when subjects with normal stereoacuity viewed the crossed disparity image as compared to the zero disparity image, although the result did not reach significance. It was also noted that most subjects showed an accommodation lag with respect to the 2.5D stimulus. Figure 6.1 compares the accommodation means of each subject under the 2 viewing conditions.

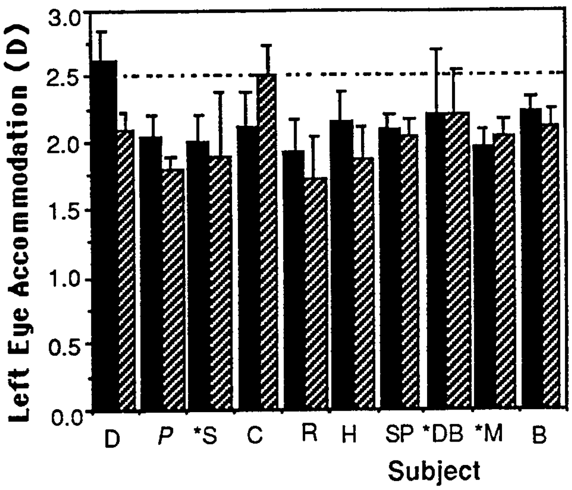


Figure 6.1: Graph comparing the mean accommodations when the subjects viewed the crossed disparity image of the "Cat" and when the subjects viewed the zero disparity image of the "Cat" of the same size and distance.

Although subject P had a TNO stereopsis of only 240 seconds of arc, his significant increase in accommodation of 0.26D is higher than that of many subjects who had stereopsis of 60 seconds of arc or better.

Figure 6.2 shows the composite accommodation mean of all the 9 subjects (excluding subject P).

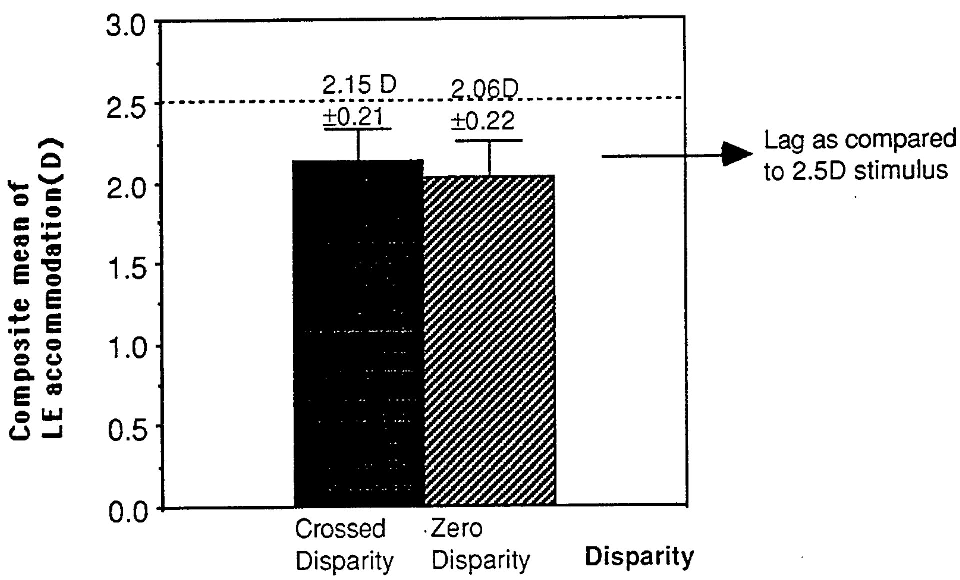


Figure 6.2: Composite means of the left eye accommodative response of all the 10 subjects under the 2 viewing conditions: Crossed-disparity image and zero-disparity image. A 1 tailed paired t-test (which only took into account the average accommodation in each subject) showed that there was no significant difference between the 2 composite means. (p = 0.15)

Part II

Appendix 6.3 gives full details of the results obtained by each subject. The part II results are summarised in Table 6.4 and 6.5.

Since there are 3 viewing conditions involved, three means. must be compared. Thus an ANOVA single factor test was used to analyse the significance of the sample means instead of the student t-test.

Comparing crossed-disparity "Butterfly" image with no-disparity "Butterfly" image

When the data of Tables 6.4 and 6.5 are considered, most subjects (7 out of 9 subjects) show an increase in accommodation when they view the crossed-disparity image of the butterfly as compared to the zero-disparity image. (i.e.the accommodation obtained when the subjects viewed the TNO chart at the same distance but without wearing any red/green goggle.) On average, the increase in accommodation is 0.07D for the 7 subjects with normal stereopsis. However only 5 out of the 9 subjects showed a significant difference in the 2 means of accommodation under the 2 viewing conditions. (See Table 6.3.) Of these 5 subjects, subject N had significantly lower accommodation when viewing the crossed disparity image.

Subject	p-values	F crit	df
V	0.009	4.11	37
MH	*0.146	4.1	39
AS	*0.41	4.23	27
AC	<0.001	4.11	37
AB	*0.85	4.1	39
N	0.011	4.11	37
RF	0.005	4.2	29
RN	*0.18	4.15	33
RS	0.03	4.13	35

*Table 6.3: Indicates the p values, F critical values and degree of freedom (df) from the ANOVA single-factor test to compare the accommodation means between the 2 viewing conditions: Viewing images of crossed disparity and zero disparity. * indicates that the 2 means are not significantly different. The significance level at which the critical values of the F statistic are evaluated is 0.05.*

Subjects AS and RF had subnormal stereopsis of 240 second of arc and 120 second of arc respectively. Unlike subject P in part I, subject AS did not show any significant change in accommodation between the two viewing conditions. Subject RF, however, showed a significant increase in accommodation when she viewed the crossed-disparity image as compared to the zero-disparity image. Moreover, her increase of 0.27D was the second highest among the 9 subjects.

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity Image		
Subject	Sph.	Cyl.	Eff. Sph	Sph.	Cyl.	Eff. Sph.	Sph.	Cyl.	Eff. Sph.
V	1.05	1.39	1.74	1.00	1.03	1.51	0.97	1.23	1.59
MH	1.63	0.90	2.08	1.60	0.46	1.83	1.77	0.77	2.16
AS	*1.46*	*0.94*	*1.93*	*1.52*	*0.78*	*1.91*	*1.49*	*0.74*	*1.86*
AC	2.49	0.67	2.83	2.03	0.77	2.42	2.08	0.69	2.43
AB	1.77	0.32	1.93	1.23	0.39	1.42	1.55	0.71	1.90
N	1.16	0.96	1.64	0.95	0.61	1.26	1.33	1.11	1.89
RF	*1.22*	*1.31*	*1.88*	*1.22*	*0.99*	*1.71*	*1.21*	*0.80*	*1.61*
RN	1.92	0.52	2.18	1.80	0.40	2.00	1.83	0.52	2.09
RS	2.02	0.35	2.19	1.95	0.35	2.12	1.91	0.30	2.06
Mean	1.72	0.73	2.08	1.51	0.57	1.79	1.63	0.76	2.02

Table 6.4: Average accommodation of the left eye as measured by the auto-refractor when the subjects viewed the "Butterfly" with crossed and uncrossed disparity of 1200 seconds of arc and with zero disparity Subjects AS and RF's results are excluded in the computation of the mean because of their subnormal stereopsis

<u>Comparing responses to an uncrossed-disparity "Butterfly" image with those for a zero-disparity "Butterfly" image</u>

Uncrossed disparity of the "Butterfly" image was obtained by viewing the TNO Chart upside down with the red/green goggle. In this viewing condition, 6 out of the 9 subjects showed a decrease in accommodation when comparied to their accommodation when viewing the TNO chart at the same distance but without wearing any red/green goggle. The average decrease of accommodation of the 7 subjects with normal stereopsis was 0.22D. Both subjects with subnormal stereopsis did not show any significant change in accommodation (Table 6.5)

Subject	Difference in Accommodation between viewing of crossed and zero disparity of image	Difference in Accommodation between viewing of uncrossed and zero disparity of image	Difference in Accommodation between viewing of crossed and uncrossed disparity of image
V	0.15D	*-0.08D	0.23D
MH	*-0.08D	-0.33D	0.25D
AS	**0.08D*	**0.05D*	**0.02D*
AC	0.40D	*-0.01D	0.41D
AB	*0.02D	-0.48D	0.51D
N	-0.25D	-0.63D	0.38D
RF	*0.27D*	**0.10D*	*0.17D*
RN	*0.09D	*-0.09D	0.18D
RS	0.13D	*0.06D	*0.07D
Mean	0.07D	-0.22D	0.29D

*Table 6.5: Table showing the differences in accommodation between the 3 viewing conditions. Generally there was an increase in accommodation (indicated by the positive sign) when the subjects viewed the crossed disparity image as compared to zero disparity image; there was a decrease in accommodation when the subjects viewed uncrossed disparity image as compared to zero disparity image; and an increase in accommodation when the subjects viewed the crossed disparity image as compared to uncrossed disparity image. * indicated that the difference is non significant. Subjects AS and RF's results are excluded in the computation of the mean because of their subnormal stereopsis.*

Subject	p-values	F crit	df
V	*0.164	4.11	37
MH	<0.001	4.1	39
AS	*0.368	4.23	27
AC	*0.934	4.11	37
AB	<0.001	4.1	39
N	<0.001	4.11	37
RF	*0.292	4.2	29
RN	*0.154	4.15	33
RS	*0.336	4.13	35

*Table 6.6: Indicates the p values, F critical values and degree of freedom (df) from the ANOVA single-factor test to compare the accommodation means between the 2 viewing conditions: Viewing images of uncrossed disparity and zero disparity. * indicates that*

the 2 means are not significantly different. The significance level at which the critical values of the F statistic are evaluated is 0.05.

When an ANOVA single-factor test was done on the means of accommodation between the 2 viewing conditions, less than half of the subjects (3 out of 9 subjects) showed a significant difference in the means. Refer to Table 6.6.

<u>Comparing the accommodation with the crossed-disparity "Butterfly" image with that for the uncrossed-disparity "Butterfly" image</u>

All 9 subjects showed an increase in accommodation when the eyes viewed the crossed disparity image as compared to the uncrossed disparity image, even though the TNO chart was placed at the same distance from the eyes in these 2 viewing conditions. The average increase in accommodation for the 7 subjects with normal stereopsis was 0.25D. Of these 7 subjects, 6 showed a significant increase in accommodation. Both subjects, AS and RF, with subnormal stereopsis showed no significant difference in their accommodation means. (Refer to Table 6.7)

Subject	p-values	F crit	df
V	<0.001	4.11	37
MH	<0.001	4.1	39
AS	*0.796	4.23	27
AC	<0.001	4.11	37
AB	<0.001	4.1	39
N	<0.001	4.11	37
RF	*0.097	4.2	29
RN	0.001	4.15	33
RS	*0.152	4.13	35

*Table 6.7: The p values, F critical values and degree of freedom (df) from the ANOVA single-factor test to compare the accommodation means between the 2 viewing conditions: Viewing images of crossed disparity and uncrossed disparity. * indicates that the 2 means are not significantly different. The significance level at which the critical values of the F statistic are evaluated is 0.05.*

Figure 6.3 compares the accommodation means for all 9 subjects among the 3 viewing conditions. The ANOVA single-factor was used to test the significance of the differences between the three accommodation means under the 3 viewing conditions

(viewing of crossed-disparity image, zero-disparity image and uncrossed-disparity image). See Table 6.8.

Subject	p-values	F crit	df
V	<0.001	3.17	56
MH	<0.001	3.16	59
AS	*0.613	3.24	41
AC	<0.001	3.17	56
AB	<0.001	3.16	59
N	<0.001	3.17	56
RF	0.021	3.22	44
RN	0.016	3.19	50
RS	*0.075	3.18	53

*Table 6.8: The p values, F critical values and degree of freedom (df) from the ANOVA single-factor test to compare the three accommodation means from the 2 viewing conditions: Viewing images of crossed disparity, zero disparity and uncrossed disparity. * indicates that the 3 means are not significantly different. The significance level at which the critical values of the F statistic are evaluated is 0.05.*

Figure 6.4 shows the composite accommodation means of 7 subjects (excluding subjects AS and RF) among the 3 viewing conditions. As in the part I result, the composite accommodation means show an accommodation lag. Though the three composite means are not significantly different, they show the following trend: the composite accommodation mean for viewing the uncrossed disparity image was the highest, followed that for the zero disparity image, with the lowest accommodation being exercised for the crossed disparity image.

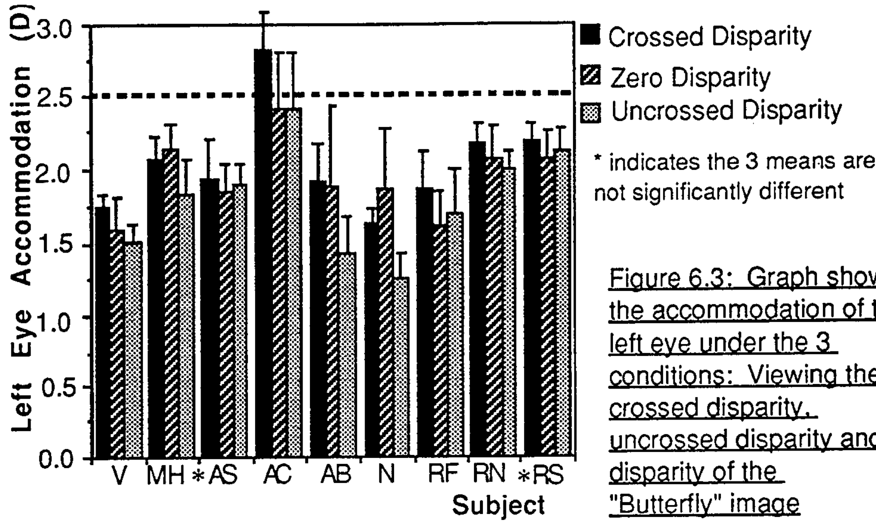


Figure 6.3: Graph showing the accommodation of the left eye under the 3 conditions: Viewing the crossed disparity, uncrossed disparity and no disparity of the "Butterfly" image

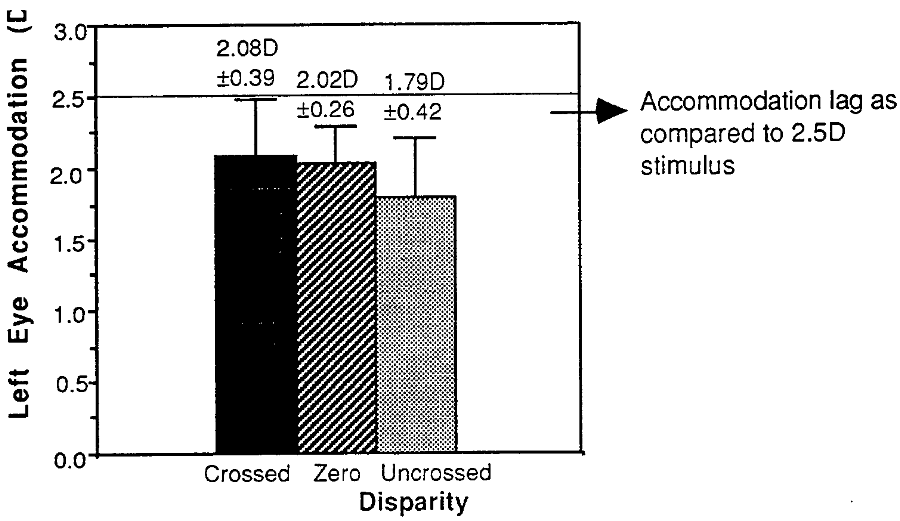


Figure 6.4: Graph showing the composite means of all the subjects left eye accommodation under 3 viewing conditions: Viewing the crossed disparity, zero disparity and uncrossed disparity images of the "Butterfly" in the TNO stereopsis chart. ANOVA single-factor showed that the 3 composite accommodation means are not significantly different. ($p = 0.318$, F critical = 3.55, degree of freedom = 20; the significant level at which the critical values of the F statistic are evaluated is 0.05.) (Subject AS and RF's results are excluded)

6.4. Discussion

The disparities the Lang-Stereotest "Cat" and the TNO "Butterfly" were 1200 seconds of arc when the charts were viewed at 40 cm. Assuming the pupillary distance (P) of all the subjects was 6.5 cm, we can calculate the distances d_f and d_b of the crossed and uncrossed disparity images from the stereogram charts respectively. With d_f and d_b known, we can calculate the perceive distances of the 3-D images and

compare it with the subjects' accommodations. Since stereoacuity is the same for the TNO "Butterfly" when it is viewed at the right side up and upside down, d_f and d_b have the same value. For convenience, only d_f for the crossed disparity image will be calculated. Figure 6.5 shows the relevant angles and distances.

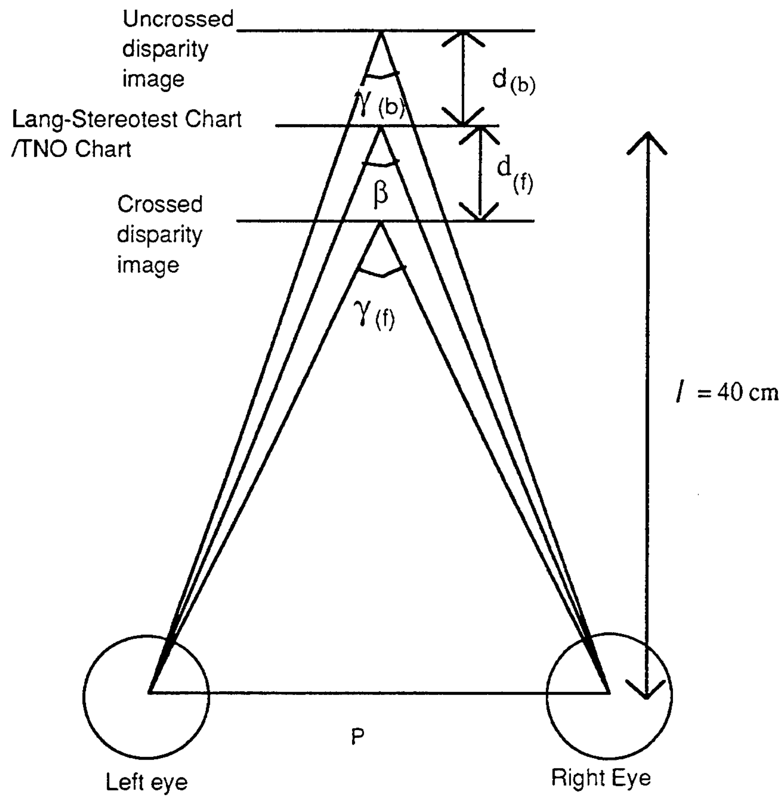


Figure 6.5: Schematic drawing (not to scale) to show the positions of the projected 3-D images and the Lang-Stereotest/TNO Charts (with disparities of 1200 seconds of arc) from the eyes

<u>Calculations</u>

To find d_f for the crossed disparity image. The assumption is made that all angles are small

Stereoacuity = g_f - b

Stereoacuity = $[P/(l - d_f)] - [P/l]$ rads

Stereoacuity = $(Pl - Pl + Pd_f) / (l^2 - ld_f)$ rads

Stereoacuity = Pd_f / l^2 rads., since $ld_f << l^2$

Stereoacuity is given as 1200 second of arc, thus

$1200 = (Pd_f / l^2) \times [(180 \times 60 \times 60)/\pi]$

l is given as 40 cm and assuming P is 6.5 cm, thus

$1200 = (6.5 \times d_f \times 180 \times 60 \times 60) / (40^2 \times \pi)$

$d_f = (1200 \times 40^2 \times \pi) / (6.5 \times 180 \times 60 \times 60)$

$d_f = 1.43$ cm.

Therefore the crossed-disparity images of the "Cat" and "Butterfly" should be perceived to be at (40 cm - 1.43 cm) = 38.57 cm from the eyes, i.e. at a vergence of -2.59D. At 40 cm, where the stereogram charts were placed, the dioptric distance was 2.50D. Thus an increase of (2.59D - 2.50D) = 0.09D of accommodation would be expected when the subjects perceived the crossed disparity images.

Since d_f was equal to d_b, the uncrossed disparity image was perceived to be (40 cm + 1.43 cm) = 41.43 cm from the eyes of the subject. 41.43 cm was equivalent to 2.41D. Thus the expected decrease in accommodation when the subjects viewed the stereogram at 40 cm and the uncrossed disparity image was (2.50D - 2.41D) = 0.09D.

The dioptric distances between the perceived front projected and back projected images from the eyes were 2.59D and 2.41D. Thus the difference in expected accommodation when the subjects viewed the cross and uncross disparity image would be approximately (2.59D - 2.41D) = 0.18D.

Tables 6.9 and 6.10 summarise the experimental results found for normal subkjects, allowing comparison with the theoretical predictions, It can be seen that, at least for small disparity images, the 3-D percept provided by the crossed or uncrossed disparity does drive accommodation in the expected direction. and by approximately the expected amounts This is in spite of the fact that, in principle, such a accommodation change may defocus the retinal images of the 2-D stimulus. Since, however, the accommodation changes in the present case were quite small, (about 0.1D), any defocus effect was probably not significant. It might be expected that with larger disparities, normally demanding higher levels of accommodation and convergence, the problems of retinal image defocus might be more acute, leading to a mismatch between nominal accommodation demand and the accommodation achieved.

		Observed	
	Calculated	Part I	Part II
Crossed Disparity	2.59D	2.15D	2.08D
Zero Disparity	2.50D	2.03D	2.02D
Uncrossed Disparity	2.41D		1.79D

Table 6.9: Summary of result. Indicates the expected calculated accommodation required in order to view the 3 different images and the actual accommodation (composite means) recorded by our subjects with normal stereopsis.

	Expected Calculated Difference	Observed Part I	Difference Part II
Crossed - zero disparity	0.09D	0.09D	0.07D
Uncrossed - zero disparity	-0.09D		-0.23D
Crossed - Uncrossed disparity	0.18D		0.29D

Table 6.10: Indicates the expected difference in accommodation between the various pairs of viewing conditions and the actual difference (deduced from the composite means) in accommodation recorded by our subjects with normal stereopsis.

Figure 6.6 shows the results of the 3 subjects who had subnormal stereopsis. (P 240 sec arc; AS 240 sec arc; RF 120 sec arc;, all on TNO test) From the graph, accommodation for AS is not significantly different among the three viewing conditions. However, P and RF have quite similar trends of accommodative responses to those of the subjects with normal stereopsis. It could be argued that though subject RF has subnormal stereopsis of 120 seconds of arc, her stereopsis is still much better than subject AS (240 seconds of arc) and thus she could accommodate to the disparity images. But subject P also has the same stereopsis as subject AS, and yet he shows a significant increase in accommodation when he viewed the crossed disparity image.

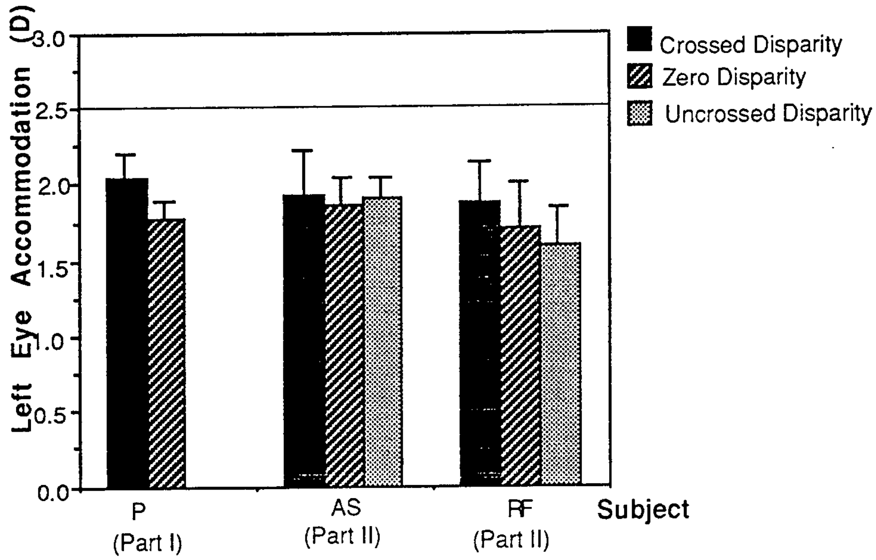


Figure 6.6: Accommodations of those subjects with subnormal stereopsis when they viewed crossed, uncrossed and zero disparity images. Subject P participated in Part I and subject AS and RF participated in the Part II of the experiment.

6.4. Conclusions

1. Most subjects tended to accommodate significantly more (10 out of 19 subjects: 6 out of 10 in part I and 4 out of 9 in part II) when they perceived the crossed-disparity image from the stereogram chart which was situated farther away and where the eyes were converging. The composite change in mean difference in accommodation was quite similar to the change in accommodation. expected on the basis of the disparity of the stereoscopic images.

2. When subjects viewed an uncrossed-disparity image, most (6 out of 9 subjects) showed no significant change in accommodation as compared to viewing the stereogram chart. The mean difference in accommodation was, however, of about the magnitude expected theoretivcally.

3. Most subjects (6 out of 9 subjects) showed a significant change in accommodation when accommodation to a crossed-disparity image was compared to that for an uncrossed-disparity image. Again , the exact composite change in mean accommodation (0.29D) was quite similar to the expected change in accommodation. (0.18D)

4. Only 3 subjects with subnormal stereopsis were used and these did not all respond in the same way, so that no firm conclusions can be drawn about this type of subject. It appeared, however, that at least two of them were responding with appropriate accommodation to the supra-threshold (1200 sec arc) disparities of the stereo pairs used.

CHAPTER 7 : SUMMARY

The work described in this report clarifies at least some aspects of size and distance judgements in relation to practical problems, particularly the possible spatial misjudgements experienced by aircraft flightcrew.

7,1 General Conclusions

The conclusions reached can be summarised as folows.

7.1.1. Accommodation-dependent changes in retinal image size for objects of constant angular subtense

As discussed in Chapter 2, theoretical models of the eye lend little support for the idea that such changes in retinal image size can be responsible for the very substantial errors that are reported in perceived size. Although it might be argued that currernt models of the eye involve a number of approximations, the absence of pronounced change in retinal image size is supported by the after-image experiments described in 3.2.4. For an accommodation change of up to 5 D the upper limit for any change in the size of the retinal image was about 7%., with the probable value being much smaller than this.

7.1.2 Perception of objects in free space

The size-matching experiments described in Chapter 3 give useful insights into many of the factors that affect judgements of the size of objects at various distances As the available cues to true object distance are reduced, judgements of the lateral dimensions of an object gradually change from those based on size constancy to those based on angular subtense This is nicely illustrated by the relative changes in the weighting factors C_V and C_C (Table 3.4).. The weighting for visual angle C_V gradually increases at the expense of C_S as viewing is changed from binocular to monocular, the field is restricted and finally the pupil is artificially reduced It is only fair to state that these general results are foreshadowed by the work of many earlier authors (e.g.Holway and Boring, 1941) The accommodation measurements described in 3.3.2 emphasise that the differences in size judgements found in binocular and monocular conditions are unlikely to be due to accommodation differences.

7.1,3 Looming

Although only preliminary, the looming experiments (Chapter 4) suggest that dynamic changes in angular subtense of environmental features during approach could potentially cause transient shifts in accommodation. and, possibly, convergence. At present, not enough is known about the factors influencing such accommodation changes to allow judgement to be made about whether they might impact on spatial judgements.

7,1.4. Aniso-accommodation

It has from time to time been suggested in the past that the unequal accommodation demands made during lateral fixation may have led to humans developing the ability to accomodate unequally for the two eyes. Such an ability would be an asset in allowing a user of binocular instruments and devices such as HMDs to overcome any slight maladjustments in the equality of the focusing demands for the two eyes. However, the experimental work of Chapter 5 gave no support for the existence of systematic aniso-accommodation .

7.1.5 Accommodation to stereo images

The measurements with stereo test plates with disparities of 1200 arc sec showed clearly that subjects' accommodation responded to the 3-D percept by the amount expected theoretically. The theoretical and observed shifts were, however, small (about 0.1 D) and it remains to be demonstrated that larger disparities would elicit shifts which were large enough to significantly degrade the retinal images

7.2. **Suggestions for further work**

Although the present results are useful , many questions remain to be answered. Useful areas for further potential experiments include:

(i) Size-matching experiments at larger target distances. In the present study, short target distances were used in order that the effects of substantially different levels of accommodation could be explored. In practical flight problems, however, size judgements will normally be made at much larger distances. Further work to extend the distance parameter range of the experiments in Chapter 3 would therefore be desirable.

(2) Looming studies. As discussed in Chapter 4, while it is known in general terms that change in target subtense can stimulate changes in accommodation and convergence, our knowledge of the influence of different target parameters on the induced changes is rather meagre. A full study along the lines suggested in Chapter 4 should give a much clearer idea of the likely impact of this phenomenon on the perceptual judgements of flightcrew.

(3) Accommodation to virtual reality/stereo imagery. The simple experiments of Chapter 6 indicated that, for stereo displays involving only small disparities, accommodation was driven away from thre plane of the display towards that of the perceived relief image. An important question, then, is whether larger disparities would result in even larger errors in accommodation which in turn might lead to losses in spatial resolution or visual fatigue. It would be relatively straightforward to use computer-generated stereo images with larger disparities to explore this problem further.

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Appendix 3.1

Mean results for individual subjects participating in the experiments described in section 3.2.2

Subject	3m Target	1m Target	0.50m Target	0.33m Target	0.25m Target	0.20m Target
LH	2.81±0.06	1.40±0.04	1.41±0.05	1.39±0.05	1.31±0.04	1.14±0.05
N	3.15±0.07	1.58±0.08	1.12±0.05	0.90±0.04	0.66±0.04	0.57±0.02
A	2.43±0.09	1.23±0.07	0.55±0.04	0.45±0.04	0.36±0.07	0.34±0.02
AW	2.61±0.06	1.41±0.08	1.29±0.05	0.97±0.05	0.64±0.08	0.64±0.07
S	2.82±0.02	1.27±0.02	0.95±0.06	0.74±0.04	0.47±0.02	0.56±0.02
Mean	2.76	1.38	1.06	0.89	0.69	0.65

Result for the 2nd part of the experiment: Means and standard deviations of the sidelengths of the square comparison target at 2m(expressed in degrees subtense at the cornea) required to match 2.00 degree subtense standard targets at the distances indicated. Viewing condition: Binocular observation, natural pupils, no restrictions on field of view.

Subject	3m Target	1m Target	0.50m Target	0.33m Target	0.25m Target	0.20m Target
LH	2.33±0.08	1.65±0.02	1.60±0.03	1.45±0.01	1.39±0.04	1.25±0.02
N	2.66±0.07	1.72±0.05	1.63±0.06	1.37±0.06	0.94±0.06	0.89±0.04
A	2.35±0.20	1.28±0.09	0.76±0.08	0.56±0.04	0.35±0.03	0.42±0.04
AW	2.60±0.15	1.51±0.09	1.54±0.05	1.30±0.05	0.76±0.05	0.82±0.04
S	2.42±0.07	1.54±0.01	1.45±0.02	1.03±0.05	0.71±0.07	0.91±0.07
Mean	2.47	1.54	1.40	1.14	0.83	0.86

Means and standard deviations of the sidelengths of the square comparison target at 2m (expressed in degrees subtense at the cornea) required to match 2.00 degree subtense standard targets at the distances indicated. Viewing condition: Monocular observation, natural pupil, no restriction on view of view.

Subject	3m Target	1m Target	0.50m Target	0.33m Target	0.25m Target	0.20m Target
LH	2.26±0.03	1.89±0.02	1.84±0.04	1.74±0.10	1.61±0.06	1.31±0.04
N	2.31±0.12	1.82±0.09	1.64±0.08	1.40±0.07	1.56±0.10	1.40±0.09
A	2.16±0.07	1.71±0.06	0.91±0.07	0.58±0.07	0.46±0.03	0.44±0.06
AW	2.22±0.05	1.91±0.02	2.16±0.09	1.68±0.10	1.49±0.05	1.51±0.05
S	2.47±0.09	1.60±0.04	1.54±0.04	1.38±0.06	1.04±0.05	1.00±0.03
Mean	2.28	1.79	1.62	1.36	1.23	1.13

Means and standard deviations of the sidelengths of the square comparison target at 2 m (expressed in degrees subtense at the cornea) required to match 2.00 degree subtense standard targets at the distances indicated. Viewing condition: Monocular observation, natural pupil, restriction on field of view.

Subject	3m Target	1m Target	0.33m Target	0.20m Target
LH	2.16±0.02	1.89±0.05	1.76±0.06	1.67±0.04
G	1.83±0.06	1.89±0.03	1.82±0.03	NA
A	2.68±0.11	1.55±0.08	1.46±0.12	1.49±0.11
S	2.34±0.11	1.58±0.04	1.46±0.05	1.49±0.05
N	2.56±0.07	1.91±0.03	1.65±0.08	1.56±0.12
Mean	2.31	1.76	1.63	1.55

Subtenses of matching square comparison target at 2m as a function of the distance of the two-degree subtense standard target for 5 subjects. Viewing condition: 1 mm diameter artificial pupil, monocular observation, and partial restriction of field of view

Appendix 5.1

Subjects visual information

Subject N (26 years, female)
Rx : RE -2.00DS VA 6/5
LE -2.25DS VA 6/5
Amp. of accommodation: RE 9.00D, LE 9.00D
Dark focus (RE): -1.946D (SD 0.574)
Right eye dominant.
note: Subject was wearing soft contact lens during the experiment.

Subject SB (24 years, male)
Rx: RE -0.75DS VA (6/5)
LE -0.25DS VA (6/5)
Amp. of accommodation: 10D
Dark focus (RE): -0.879D (SD 0.205)
Right eye dominant.
note: Subject was not wearing any correction during the experiment.

Subject RS (20 years, female)
Rx: RE -6.50DS +1.25DC x 90 VA 6/6
LE -6.25DS +0.75DC x 90 VA 6/6
Amp. of accommodation: 11.50D
Dark focus (RE): -3.467D (SD 1.247)
Right eye dominant
note: Subject was wearing RGP contact lens during the experiment. A -0.50DS was required on the LE to enable her to see the 6/6 line.

Subject S (25 years, male)
Rx: RE -1.00DS VA 6/5
LE -0.75DS VA 6/5
Amp. of accommodation: RE 10.0D, LE 10.00D
Dark focus (RE): -1.649D (SD 0.601)
Left eye dominant
note: Subject was wearing spectacle correction during the experiment.

Subject AD (24 years, male)
Rx RE Plano VA 6/5
LE Plano VA 6/5
Amp. of accommodation: RE 10.00D, LE 10.00D
Dark focus: +0.166D (SD 0.263)
Right eye dominant

Subject AW (19 years old, male)
Rx: RE -0.25DS VA 6/6
LE Plano VA 6/6
Amp. of accommodation: RE 11.00D, LE 11.00D (Using Sheard's method)
Dark focus: -0.447D (SD 0.191)
note: subject was not wearing any correction during the experiment.

Appendix 5.2

SUBJECT: SB
AGE 24 YEARS
PRESC RE -0.75DS VA 6/6
LE -0.25DS VA 6/6
AMP. OF ACCOMMODATION: 10D (PUSH UP METHOD)
NOTE: THE SUBJECT WAS NOT WEARING ANY CORRECTION DURING THE EXPERIMENT. SUBJECT IS RE DOMINANT.

	0			-0.25			-0.5			-0.75			-1			-1.25		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	-0.37	-0.5	-0.62	-0.25	-0.75	-0.625	-0.5	-0.5	-0.75	-0.75	-0.37	-0.935	-0.5	-0.62	-0.81	-0.62	-0.5	-0.87
	-0.5	-0.62	-0.81	-0.25	-0.75	-0.625	-0.37	-0.75	-0.745	-0.5	-0.62	-0.81	-0.5	-0.75	-0.875	-0.5	-0.75	-0.875
	-0.5	-0.37	-0.685	-0.5	-0.37	-0.685	-0.5	-0.37	-0.685	-0.5	-0.75	-0.875	-0.5	-0.75	-0.875	-0.5	-0.75	-0.875
	-0.37	-0.75	-0.745	-0.5	-0.37	-0.685	-0.37	-0.75	-0.745	-0.5	-0.62	-0.81	-0.5	-0.62	-0.81	-0.62	-0.75	-0.995
	-0.37	-0.62	-0.68	-0.25	-0.62	-0.56	-0.37	-0.62	-0.68	-0.37	-0.87	-0.805	-0.5	-0.62	-0.81	-0.62	-0.62	-0.93
	-0.37	-0.62	-0.68	-0.37	-0.62	-0.68	-0.37	-0.62	-0.68	-0.37	-0.87	-0.805	-0.5	-0.62	-0.81	-0.62	-0.62	-0.93
	-0.5	-0.62	-0.81	-0.37	-0.62	-0.68	-0.37	-0.62	-0.68	-0.5	-0.75	-0.875	-0.5	-0.62	-0.81	-0.62	-0.62	-0.93
	-0.5	-0.37	-0.685	-0.37	-0.75	-0.745	-0.37	-0.62	-0.68	-0.37	-0.62	-0.68	-0.5	-0.62	-0.81	-0.62	-0.62	-0.93
	-0.37	-0.62	-0.68	-0.37	-0.75	-0.745	-0.25	-0.62	-0.56	-0.5	-0.62	-0.81	-0.5	-0.62	-0.81	-0.62	-0.62	-0.93
	-0.37	-0.62	-0.68	-0.37	-0.75	-0.745	-0.37	-0.75	-0.745	-0.5	-0.62	-0.81	-0.5	-0.62	-0.81	-0.62	-0.62	-0.93
	-0.37	-0.37	-0.555	-0.37	-0.75	-0.745	-0.37	-0.75	-0.745	-0.37	-0.62	-0.68	-0.5	-0.62	-0.81	-0.75	-0.62	-1.06
	-0.37	-0.62	-0.68	-0.25	-0.75	-0.625	-0.37	-0.75	-0.745	-0.5	-0.62	-0.81	-0.5	-0.62	-0.81	-0.75	-0.62	-1.06
MEAN	-0.413	-0.56	-0.693	-0.352	-0.65	-0.678	-0.382	-0.64	-0.703	-0.478	-0.68	-0.808	-0.5	-0.64	-0.821	-0.622	-0.64	-0.943
SD	0.064	0.125	0.071	0.088	0.144	0.061	0.065	0.118	0.058	0.108	0.135	0.073	0.000	0.051	0.025	0.075	0.073	0.084

	-1.5			-1.75			-2			-2.25			-2.5			-2.75			-3		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	-0.62	-0.5	-0.87	-0.62	-0.5	-0.87	-0.5	-0.62	-0.81	-0.5	-0.62	-0.81	-0.62	-0.25	-0.745	-0.5	-0.37	-0.685	-0.75	-0.62	-1.06
	-0.87	-0.5	-1.12	-0.62	-0.75	-0.995	-0.5	-0.75	-0.875	-0.37	-1	-0.87	-0.5	-0.62	-0.81	-0.37	-0.75	-0.745	-0.37	-0.75	-0.745
	-0.62	-0.62	-0.93	-0.87	-0.75	-1.245	-0.5	-0.62	-0.81	-0.37	-0.75	-0.745	-0.62	-0.5	-0.87	-0.37	-0.75	-0.745	-0.25	-1.12	-0.81
	-0.62	-0.75	-0.995	-0.75	-0.75	-1.125	-0.5	-0.62	-0.81	-0.37	-0.87	-0.805	-0.62	-0.5	-0.87	-0.25	-0.62	-0.56	-0.5	-0.75	-0.875
	-0.62	-0.62	-0.93	-0.87	-0.75	-1.245	-0.5	-0.75	-0.875	-0.37	-0.87	-0.805	-0.62	-0.5	-0.87	-0.37	-0.62	-0.68	-0.5	-0.75	-0.875
	-0.62	-0.62	-0.93	-0.75	-0.75	-1.125	-0.75	-0.62	-1.06	-0.62	-0.87	-1.055	-0.37	-0.87	-0.805	-0.5	-0.87	-0.935	-0.5	-0.62	-0.81
	-0.62	-0.5	-0.87	-0.75	-0.87	-1.185	-0.75	-0.75	-1.125	-0.62	-0.87	-1.055	-0.37	-0.75	-0.745	-0.5	-0.75	-0.875	-0.5	-0.62	-0.81
	-0.62	-0.75	-0.995	-0.62	-1	-1.12	-0.87	-0.62	-1.18	-0.75	-1	-1.25	-0.5	-0.75	-0.875	-0.5	-0.75	-0.875	-0.87	-0.5	-1.12
	-0.62	-0.75	-0.995	-0.62	-0.87	-1.055	-0.75	-0.62	-1.06	-0.75	-1	-1.25	-0.5	-0.62	-0.81	-0.5	-0.75	-0.875	-0.5	-0.75	-0.875
	-0.75	-0.62	-1.06	-0.75	-0.87	-1.185	-0.62	-0.75	-0.995	-0.62	-0.87	-1.055	-0.5	-0.62	-0.81	-0.5	-0.62	-0.81	-0.5	-0.75	-0.875
	-0.62	-0.5	-0.87	-0.75	-0.87	-1.185	-0.5	-0.75	-0.875	-0.62	-1	-1.12	-0.5	-0.75	-0.875	-0.5	-0.75	-0.875	-0.37	-0.75	-0.745
	-0.62	-0.5	-0.87	-0.75	-0.75	-1.125	-0.5	-0.62	-0.81	-0.62	-0.87	-1.055	-0.25	-1	-0.75	-0.5	-0.62	-0.81	-0.37	-0.75	-0.745
Mean	-0.652	-0.6	-0.953	-0.727	-0.79	-1.122	-0.603	-0.67	-0.94	-0.548	-0.88	-0.99	-0.488	-0.64	-0.82	-0.447	-0.69	-0.789	-0.498	-0.73	-0.862
SD	0.078	0.104	0.082	0.090	0.122	0.107	0.139	0.067	0.172	0.147	0.114	0.177	0.119	0.198	0.052	0.085	0.128	0.109	0.169	0.149	0.119

	pair 2 tail t-test to determine if there is any difference in accommodation when one eye has no negative sphere.											
sphere	-0.25	-0.5	-0.75	-1	-1.25	-1.5	-1.75	-2	-2.25	-2.5	-2.75	-3
p value	0.855	0.685	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.035	0.002

	Negative spheres which simulated a significant change in accommodation.(DS)									
	-0.75	-1	-1.25	-1.5	-1.75	-2	-2.25	-2.5	-2.75	-3
Significant change in accommodation	0.1183	0.1283	0.25	0.2604	0.4292	0.248	0.2971	0.1271	0.097	0.1696

SUBJECT: AD
AGE 24 YEARS
PRESC RE PLANO VA 6/6
LE PLANO VA 6/6
AMP. OF ACCOMMODATION: 10.00D
NOTE: THE SUBJECT WAS NOT WEARING ANY CORRECTION DURING THE EXPERIMENT. SUBJECT IS RE DOMINANT.

	0			-0.25			-0.5			-0.75			-1			-1.25			-1.5			-1.75		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0.25	-0.37	0.065	0.25	-0.5	0	0.25	-0.62	-0.06	0.12	-0.5	-0.13	-0.25	-0.25	-0.375	0.5	-0.5	0.25	0.12	-0.37	-0.065	0	-0.62	-0.31
	0.25	-0.25	0.125	0.12	-0.5	-0.13	0.12	-0.62	-0.19	0.12	-0.5	-0.13	0	-0.37	-0.185	0.37	-0.5	0.12	0.25	-0.5	0	1.25	-1.75	0.375
	0.25	-0.37	0.065	0.12	-0.5	-0.13	0.12	-0.62	-0.19	0.12	-0.5	-0.13	0	-0.25	-0.125	0.25	-0.5	0	0.25	-0.37	0.065	0.25	-0.37	0.065
	0.37	-0.25	0.245	0.25	-0.5	0	0	-0.62	-0.31	0.12	-0.5	-0.13	0.12	-0.5	-0.13	1	-0.87	0.565	0.25	-0.5	0	0.5	-0.37	0.315
	0	-0.37	-0.185	0.12	-0.5	-0.13	-0.12	-0.62	-0.43	0.12	-0.5	-0.13	-0.12	-0.37	-0.305	0.37	-0.5	0.12	0.012	-0.25	-0.113	0.25	-0.25	0.125
	0.5	-0.37	0.315	0.12	-0.5	-0.13	0.12	-0.62	-0.19	0	-0.37	-0.185	0.37	-0.37	0.185	0.25	-0.37	0.065	0.37	-0.37	0.185	0.75	-0.37	0.565
	0.5	-0.37	0.315	0.25	-0.5	0	0	-0.62	-0.31	0	-0.37	-0.185	0.12	-0.5	-0.13	0.37	-0.37	0.185	0.12	-0.25	-0.005	0.87	-0.37	0.685
	0.5	-0.5	0.25	0.12	-0.5	-0.13	0	-0.62	-0.31	0	-0.5	-0.25	0.12	-0.37	-0.065	0.5	-0.5	0.25	0	0	0	1	-0.37	0.815
	0.12	-0.5	-0.13	0.25	-0.5	0	0.25	-0.62	-0.06	0	-0.37	-0.185	0.25	-0.37	0.065	0.87	-0.37	0.685	0	0	0	1	-0.37	0.815
	0.12	-0.5	-0.13	0.25	-0.5	0	0.12	-0.5	-0.13	0.12	-0.37	-0.065	0	-0.5	-0.25	0.12	-0.37	-0.065	0	-0.25	-0.125	1	-0.37	0.815
	0.25	-0.37	0.065	0.25	-0.5	0	0.12	-0.5	-0.13	0.25	-0.5	0	0.12	-0.37	-0.065	0.37	-0.37	0.185	0.25	-0.37	0.065	0.75	-0.37	0.565
	0.37	-0.62	0.06	0.12	-0.5	-0.13	0.25	-0.62	-0.06	0.62	-0.5	0.37	0.5	-0.5	0.25	0	-0.37	-0.185	0.12	-0.25	-0.005	0.12	-0.25	-0.005
MEAN	0.29	-0.4	0.0883	0.185	-0.5	-0.065	0.1025	-0.6	-0.198	0.1375	-0.46	-0.096	0.1025	-0.39	-0.094	0.4142	-0.47	0.1813	0.1452	-0.29	0.0002	0.645	-0.48	0.4021
SD	0.163	0.108	0.172	0.066	0.000	0.066	0.116	0.047	0.120	0.171	0.064	0.160	0.204	0.090	0.187	0.284	0.143	0.245	0.127	0.152	0.083	0.409	0.408	0.371

	-2			-2.25			-2.5			-2.75			-3			-3.25			-3.5			-3.75		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0.12	-0.37	-0.065	0	-0.62	-0.31	-0.12	-0.5	-0.37	0.12	-0.62	-0.19	0.37	-0.5	0.12	0.37	-0.25	0.245	0.25	-0.37	0.065	0.25	-0.62	-0.06
	0.37	-0.5	0.12	0	-0.37	-0.185	0.37	-0.62	0.06	0.25	-0.62	-0.06	0.12	-0.25	-0.005	0.12	-0.37	-0.065	0.25	-0.37	0.065	0.25	-0.5	0
	0.62	-0.37	0.435	0	-0.62	-0.31	0.25	-0.37	0.065	0.25	-0.5	0	0.25	-0.5	0	0.37	-0.62	0.06	0.25	-0.5	0	0.25	-0.62	-0.06
	0.75	-0.37	0.565	0	-0.5	-0.25	-0.37	-0.5	-0.62	0.62	-0.75	0.245	0	-0.37	-0.185	0.25	-0.5	0	0.12	-0.5	-0.13	0.37	-0.62	0.06
	0.5	-0.37	0.315	0	-0.62	-0.31	0	-0.5	-0.25	0.62	-0.5	0.37	0.25	-0.5	0	0.62	-0.62	0.31	0.25	-0.5	0	0.25	-0.5	0
	0.87	-0.25	0.745	0	-1	-0.5	0.25	-0.5	0	0.62	-0.5	0.37	0.5	-0.5	0.25	0.5	-0.5	0.25	0.25	-0.5	0	0.37	-0.5	0.12
	1	-0.5	0.75	0.12	-0.5	-0.13	0.25	-0.62	-0.06	0.75	-0.5	0.5	0.37	-0.5	0.12	0.62	-0.5	0.37	0.25	-0.62	-0.06	0.37	-0.5	0.12
	1	-0.37	0.815	0	-0.37	-0.185	0.37	-0.5	0.12	0.75	-0.5	0.5	0.37	-0.5	0.12	0.25	-0.37	0.065	0.25	-0.5	0	0.37	-0.5	0.12
	1	-0.37	0.815	0.12	-0.5	-0.13	0.5	-0.5	0.25	0.62	-0.5	0.37	0.25	-0.5	0	0.25	-0.5	0	0.5	-0.5	0.25	0.37	-0.5	0.12
	1	-0.37	0.815	0.12	-0.5	-0.13	0.5	-0.37	0.315	0.37	-0.5	0.12	0.25	-0.5	0	0.25	-0.5	0	0.62	-0.5	0.37	0.25	-0.5	0
	0.87	-0.37	0.685	0.12	-0.37	-0.065	0.62	-0.5	0.37	0.25	-0.75	-0.125	0.25	-0.5	0	0.25	-0.5	0	0.12	-0.5	-0.13	0.5	-0.5	0.25
	0.12	-0.37	-0.065	0.25	-0.5	0	0.5	-0.37	0.315	0.5	-0.37	0.315	0.25	-0.5	0	0.25	-0.5	0	0	-0.37	-0.185	0.37	-0.5	0.12
MEAN	0.685	-0.38	0.4942	0.0608	-0.54	-0.209	0.26	-0.49	0.0183	0.4767	-0.55	0.2013	0.2692	-0.47	0.035	0.342	-0.478	0.103	0.259	-0.478	0.020	0.331	-0.530	0.066
SD	0.337	0.065	0.389	0.083	0.172	0.135	0.282	0.084	0.302	0.218	0.113	0.244	0.128	0.078	0.107	0.160	0.104	0.149	0.164	0.073	0.158	0.080	0.054	0.092

	-4			-4.25			-4.5			-4.75			-5			-5.25			-5.5			-5.75		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	-0.12	-0.25	-0.245	0	0	0	0.25	-0.75	-0.125	0.5	-0.5	0.25	0.25	-0.37	0.065	0.37	-0.5	0.12	0.25	-0.62	-0.06	0.12	-0.37	-0.065
	0.12	-0.5	-0.13	0	0	0	0.37	-0.37	0.185	0.12	-0.25	-0.005	0	-0.5	-0.25	0.5	-0.37	0.315	0.12	-0.5	-0.13	0.25	-0.25	0.125
	0	-0.37	-0.185	0.12	-0.25	-0.005	0.25	-0.5	0	0.37	-0.37	0.185	0.12	-0.5	-0.13	0.25	-0.5	0	0.25	-0.37	0.065	0.37	-0.37	0.185
	0	-0.37	-0.185	0.12	-0.25	-0.005	0.25	-0.5	0	0.25	-0.25	0.125	0.25	-0.5	0	0.37	-0.5	0.12	0.12	-0.37	-0.065	0.25	-0.5	0
	0.12	-0.5	-0.13	0.25	-0.5	0	0.62	-0.5	0.37	0.25	-0.37	0.065	0.25	-0.5	0	0.25	-0.37	0.065	0.37	-0.5	0.12	0.25	-0.37	0.065
	0.12	-0.37	-0.065	0.25	-0.5	0	0.25	-0.5	0	0.25	-0.25	0.125	0.37	-0.5	0.12	0.62	-0.37	0.435	0.37	-0.5	0.12	0.25	-0.5	0
	0.12	-0.25	-0.005	0.12	-0.5	-0.13	0.25	-0.62	-0.06	0.37	-0.62	0.06	0.5	-0.5	0.25	0.37	-0.37	0.185	0.37	-0.5	0.12	0.5	-0.37	0.315
	0	-0.37	-0.185	0.12	-0.5	-0.13	0.37	-0.62	0.06	0.25	-0.5	0	0.5	-0.37	0.315	0.25	-0.37	0.065	0.37	-0.5	0.12	0.5	-0.5	0.25
	0.25	-0.37	0.065	0.25	-0.5	0	0.37	-0.5	0.12	0.5	-0.5	0.25	0.5	-0.5	0.25	0.5	-0.37	0.315	0.37	-0.5	0.12	0.25	-0.5	0
	0.25	-0.37	0.065	0.37	-0.5	0.12	0.5	-0.5	0.25	0.5	-0.5	0.25	0.5	-0.37	0.315	0.37	-0.37	0.185	0.37	-0.5	0.12	0.25	-0.5	0
	0.37	-0.37	0.185	0.5	-0.5	0.25	0.62	-0.5	0.37	0.62	-0.5	0.37	0.5	-0.37	0.315	0.25	-0.37	0.065	0.37	-0.5	0.12	0.25	-0.5	0
	0.25	-0.37	0.065	0.5	-0.5	0.25	0.87	-0.5	0.62	0.75	-0.5	0.5	0.37	-0.5	0.12	0.37	-0.37	0.185	0.37	-0.62	0.06	0.25	-0.5	0
MEAN	0.123	-0.372	-0.063	0.217	-0.375	0.029	0.414	-0.530	0.149	0.394	-0.426	0.181	0.343	-0.457	0.114	0.373	-0.403	0.171	0.308	-0.498	0.058	0.281	-0.436	0.073
SD	0.139	0.075	0.135	0.170	0.199	0.122	0.200	0.094	0.219	0.184	0.124	0.152	0.170	0.064	0.186	0.118	0.059	0.148	0.099	0.075	0.091	0.111	0.088	0.118

	-6			-6.5			7			-7.5			-8			-9			-10		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0.25	-0.37	0.065	-0.12	-0.37	-0.305	-0.12	-0.25	-0.245	0.12	-0.5	-0.13	-0.37	-0.37	-0.555	-0.37	-0.25	-0.495	0.12	-0.5	-0.13
	0.37	-0.37	0.185	0.12	-0.37	-0.065	0.25	-0.62	-0.06	0.25	-0.62	-0.06	0	-0.5	-0.25	0.12	-0.5	-0.13	-0.12	-0.25	-0.245
	0.62	-0.37	0.435	0	-0.25	-0.125	0.25	-0.5	0	0.25	-0.5	0	0.12	-0.37	-0.065	0.25	-0.5	0	0.25	-0.5	0
	0.37	-0.37	0.185	0.25	-0.62	-0.06	0.25	-0.5	0	0.25	-0.5	0	0.25	-0.5	0	0.25	-0.5	0	0.12	-0.5	-0.13
	0.37	-0.37	0.185	-0.12	-0.25	-0.245	0.25	-0.75	0.125	0.25	-0.5	0	0.25	-0.5	0	0.37	-0.5	0.12	0.25	-0.5	0
	0.87	-0.37	0.685	0.12	-0.37	-0.065	0.25	-0.5	0	0.25	-0.5	0	0.37	-0.5	0.12	0.62	-0.37	0.435	0.25	-0.37	0.065
	1	-0.5	0.75	0.37	-0.5	0.12	0.25	-0.5	0	0.12	-0.5	-0.13	0.37	-0.5	0.12	0.5	-0.62	0.19	0.37	-0.5	0.12
	1	-0.5	0.75	0.62	-0.37	0.435	0.37	-0.5	0.12	0.37	-0.5	0.12	0.25	-0.37	0.065	0.37	-0.37	0.185	0.25	-0.62	-0.06
	1	-0.37	0.815	0.62	-0.37	0.435	0.25	-0.5	0	0.37	-0.62	0.06	0.37	-0.37	0.185	0.62	-0.37	0.435	0.62	-0.62	0.31
	1	-0.37	0.815	0.25	-0.37	0.065	0.25	-0.5	0	0.37	-0.5	0.12	0.5	-0.5	0.25	0.87	-0.5	0.62	0.5	-0.5	0.25
	1	-0.37	0.815	0.25	-0.37	0.065	0.37	-0.5	0.12	0.62	-0.62	0.31	0.37	-0.5	0.12	0.87	-0.37	0.685	0.62	-0.5	0.37
	1	-0.5	0.75	0.37	-0.5	0.12	0.25	-0.37	0.065	0.37	-0.37	0.185	0.25	-0.37	0.065	1	-0.5	0.75	0.87	-0.62	0.56
MEAN	0.738	-0.403	0.536	0.228	-0.393	0.031	0.239	-0.458	0.010	0.299	-0.519	0.040	0.228	-0.448	0.005	0.458	-0.446	0.233	0.342	-0.498	0.093
SD	0.314	0.059	0.301	0.246	0.104	0.231	0.122	0.111	0.100	0.135	0.071	0.128	0.229	0.067	0.218	0.380	0.100	0.368	0.271	0.108	0.238

	pair 2 tail t-test to determine if there is any difference in accommodation when one eye has no negative sphere.											
sphere	-0.25	-0.5	-0.75	-1	-1.25	-1.5	-1.75	-2	-2.25	-2.5	-2.75	-3
p value	0.018	0.001	0.031	0.297	0.297	0.048	0.018	0.000	0.001	0.531	0.168	0.295
sphere	-3.25	-3.5	-3.75	-4	-4.25	-4.5	-4.75	-5	-5.25	-5.5	-5.75	-6
p value	0.808	0.434	0.858	0.057	0.424	0.546	0.251	0.733	0.188	0.638	0.749	0.001
sphere	-6.5	-7	-7.5	-8	-9	-10						
p value	0.490	0.218	0.495	0.335	0.272	0.986						

	Negative spheres which simulated a significant change in accommodation.(DS)									
	-0.25	-0.5	-0.75	-1.5	-1.75	-2	-2.25	-6		
Significant change in accommodation	0.1533	0.2858	0.184	0.0882	-0.314	-0.41	0.2871	-0.448		

SUBJECT: S
AGE 25 YEARS
PRESC RE -1.00DS VA 6/5
LE -0.75DS VA 6/5
AMP. OF ACCOMMODATION: 10.00D
NOTE: THE SUBJECT WAS WEARING CORRECTION DURING THE EXPERIMENT. SUBJECT IS RE DORMINANT.

	0			-0.25			-0.5			-0.75			-1			-1.25			-1.5			-1.75		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0	-0.5	-0.25	-0.12	-0.25	-0.245	-0.12	-0.37	-0.305	0.25	-1.12	-0.31	-0.12	-0.25	-0.245	-0.37	0	-0.37	0.12	-0.5	-0.13	0.37	-1	-0.13
	0.12	-0.75	-0.255	0	-0.37	-0.185	-0.25	0	-0.25	0.37	-0.87	-0.065	0	-0.37	-0.185	-0.12	-0.37	-0.305	0	-0.37	-0.185	0.12	-0.37	-0.065
	0.25	-0.75	-0.125	0	-0.5	-0.25	-0.37	0	-0.37	0.37	-0.75	-0.005	0	-0.25	-0.125	-0.12	-0.75	-0.495	0	-0.75	-0.375	0.37	-0.5	0.12
	0	-0.37	-0.185	0	-0.37	-0.185	-0.37	0	-0.37	0.37	-0.87	-0.085	0.25	-0.37	0.065	-0.37	-0.25	-0.495	0.12	-0.75	-0.255	-0.12	-0.37	-0.305
	0	-0.37	-0.185	0	-0.5	-0.25	-0.37	0	-0.37	0.37	-1	-0.13	-0.12	0	-0.12	-0.25	-0.25	-0.375	0.25	-0.87	-0.185	-0.12	-0.5	-0.37
	0.12	-0.25	-0.005	0.12	-0.62	-0.19	-0.37	-0.25	-0.495	0.37	-1	-0.13	0.12	-0.5	-0.13	-0.12	-0.25	-0.245	0	-0.62	-0.31	-0.12	-0.37	-0.305
	0	-0.37	-0.185	-0.12	-0.62	-0.43	-0.25	-0.25	-0.375	0.37	-1	-0.13	0	-0.37	-0.185	0	-0.62	-0.31	0.37	-0.75	-0.005	-0.12	-0.25	-0.245
	0	-0.5	-0.25	-0.12	-0.37	-0.305	-0.37	0	-0.37	0.25	-1.12	-0.31	-0.12	-0.62	-0.43	-0.25	-0.25	-0.375	0	-0.5	-0.25	-0.25	-0.37	-0.435
	0	-0.5	-0.25	-0.12	-0.62	-0.43	-0.25	-0.25	-0.375	0.25	-1	-0.25	0	-0.37	-0.185	-0.25	-0.25	-0.375	0	-0.5	-0.25	-0.12	-0.25	-0.245
	0	-0.5	-0.25	0	-0.5	-0.25	0	-0.25	-0.125	0.12	-0.62	-0.19	0	-0.25	-0.125	-0.25	0	-0.25	-0.12	-0.37	-0.305	-0.12	-0.37	-0.305
	0	-0.5	-0.25	0.12	-0.87	-0.315	0.12	-0.75	-0.255	0.12	-0.75	-0.255	0.25	-0.75	-0.125	-0.25	-0.75	-0.625	-0.12	-0.5	-0.37	0	-0.75	-0.375
	0.12	-0.5	-0.13	0	-0.87	-0.435	0.12	-1	-0.38	0.12	-1.5	-0.63	0	-0.25	-0.125	-0.25	-0.25	-0.375	0	-0.37	-0.185	0	-0.37	-0.185
MEAN	0.051	-0.488	-0.193	-0.020	-0.538	-0.289	-0.207	-0.260	-0.337	0.278	-0.987	-0.208	0.022	-0.383	-0.160	-0.217	-0.333	-0.383	0.052	-0.571	-0.234	-0.009	-0.458	-0.237
SD	0.082	0.147	0.078	0.088	0.184	0.095	0.191	0.322	0.093	0.108	0.227	0.166	0.127	0.185	0.113	0.108	0.251	0.110	0.143	0.173	0.105	0.199	0.218	0.154

	-2			-2.25			-2.5			-2.75			-3			-3.25			-3.5			-3.75		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	-0.12	-0.87	-0.555	-0.12	0	-0.12	0.12	-0.5	-0.13	0	-0.37	-0.185	-0.12	-0.5	-0.37	0	-0.37	-0.185	-0.25	-0.37	-0.435	-0.12	-0.37	-0.305
	0.25	-0.62	-0.06	0	-0.25	-0.125	0	-0.75	-0.375	-0.12	-0.37	-0.305	0	-0.25	-0.125	0	-0.5	-0.25	-0.12	0	-0.12	-0.12	-0.25	-0.245
	0.25	-0.87	-0.185	-0.12	-0.5	-0.37	0	-0.5	-0.25	0	-0.37	-0.185	0	-0.62	-0.31	0	-0.25	-0.125	-0.12	-0.25	-0.245	0.25	-0.62	-0.06
	0	-0.62	-0.31	0.12	-0.37	-0.065	0.12	-0.75	-0.255	0.12	-0.5	-0.13	0	-0.37	-0.185	-0.12	-0.37	-0.305	-0.37	0	-0.37	0.12	-0.62	-0.19
	-0.25	0	-0.25	-0.12	0	-0.12	0	-0.75	-0.375	0	-0.37	-0.185	0.12	-0.5	-0.13	0.12	-0.75	-0.255	0.25	-0.62	-0.06	0	-0.37	-0.185
	0	-0.5	-0.25	0	-0.37	-0.185	0.12	-0.5	-0.13	-0.12	-0.25	-0.245	0.12	-0.5	-0.13	0.12	-0.75	-0.255	-0.12	-0.87	-0.555	-0.12	-0.25	-0.245
	-0.25	-0.5	-0.5	0	-0.37	-0.185	0	-0.37	-0.185	-0.12	-0.25	-0.245	0	-0.5	-0.25	0.12	-1	-0.38	0.25	-0.25	0.125	0	-0.25	-0.125
	0.12	-0.75	-0.255	-0.25	-0.37	-0.435	-0.12	-0.5	-0.37	0	-0.62	-0.31	0.12	-0.37	-0.065	0.25	-1.5	-0.5	-0.25	0	-0.25	-0.12	-0.25	-0.245
	0	-0.75	-0.375	-0.12	-0.37	-0.305	-0.12	-0.5	-0.37	0.12	-0.5	-0.13	0	-0.37	-0.185	0.37	-0.75	-0.005	0	-0.37	-0.185	-0.25	0	-0.25
	0	-0.75	-0.375	-0.12	-0.25	-0.245	-0.12	-0.75	-0.485	-0.12	0	-0.12	0.12	-0.37	-0.065	-0.37	-0.5	-0.62	-0.12	-0.25	-0.245	-0.12	-1	-0.62
	-0.12	-0.25	-0.245	-0.25	-0.25	-0.375	-0.12	-0.37	-0.305	0	-0.62	-0.31	0.25	-0.87	-0.185	0	-0.25	-0.125	-0.12	-0.5	-0.37	-0.12	-0.5	-0.37
	0.25	-0.75	-0.125	-0.12	-0.25	-0.245	0	-0.5	-0.25	0	-0.25	-0.125	0.12	-0.37	-0.065	0	-0.25	-0.125	-0.12	-0.5	-0.37	-0.12	-0.87	-0.555
MEAN	0.011	-0.603	-0.290	-0.092	-0.279	-0.231	-0.010	-0.562	-0.291	-0.020	-0.373	-0.208	0.061	-0.466	-0.172	0.041	-0.603	-0.261	-0.091	-0.332	-0.257	-0.080	-0.448	-0.283
SD	0.179	0.259	0.309	0.107	0.151	0.119	0.095	0.147	0.111	0.088	0.176	0.075	0.097	0.161	0.088	0.184	0.373	0.173	0.184	0.267	0.183	0.134	0.288	0.163

	-4			-4.25			-4.5			-5			-5.5			-6			-6.5			-7		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0	-0.87	-0.435	0.12	-0.5	-0.13	0.25	-0.62	-0.06	-0.12	0	-0.12	0.75	-1.87	-0.185	-0.12	0	-0.12	-0.25	-0.37	-0.435	0	-0.25	-0.125
	-0.5	-0.5	-0.75	-0.25	-0.37	-0.435	0	-0.37	-0.185	0	-0.5	-0.25	-0.25	-0.25	-0.375	-0.12	-0.37	-0.305	0	0	0	0	-0.37	-0.185
	-0.12	-0.37	-0.305	-0.25	-0.87	-0.685	0	-0.25	-0.125	-0.12	-0.37	-0.305	0	-0.25	-0.125	-0.12	-0.25	-0.245	-0.25	-0.25	-0.375	0	-0.37	-0.185
	0.12	-0.75	-0.255	0	-0.25	-0.125	0.12	-0.37	-0.065	0	-0.25	-0.125	-0.75	0	-0.75	0	-0.37	-0.185	0.25	-0.37	0.065	0.12	-0.5	-0.13
	-0.25	-0.37	-0.435	-0.12	-0.25	-0.245	-0.25	-0.37	-0.435	0	-0.25	-0.125	-0.12	-0.25	-0.245	0	-0.37	-0.185	0	-0.5	-0.25	0.25	-0.62	-0.06
	0	-0.37	-0.185	-0.12	0	-0.12	-0.12	-0.25	-0.245	-0.12	-0.25	-0.245	0.12	-0.5	-0.13	0.12	-0.5	-0.13	0.12	-0.5	-0.13	0.25	-0.5	0
	0	-0.37	-0.185	0	-0.37	-0.185	-0.12	-0.25	-0.245	0	-0.62	-0.31	0.12	-0.62	-0.19	0.25	-0.5	0	0	-0.37	-0.185	0.25	-0.5	0
	0	-0.37	-0.185	0.12	-0.37	-0.065	-0.12	-0.25	-0.245	0	-0.5	-0.25	0.5	-0.62	0.19	0.25	-0.37	0.065	0.12	-0.87	-0.315	0.12	-0.5	-0.13
	0	-0.5	-0.25	0	-0.37	-0.185	-0.12	-0.37	-0.305	0	-0.62	-0.31	0.37	-1	-0.13	0.25	-0.75	-0.125	0	-0.62	-0.31	0.37	-0.62	0.06
	0.25	-0.87	-0.185	0	-0.37	-0.185	-0.37	0	-0.37	0	-0.5	-0.25	0.12	-0.75	-0.255	-0.12	-0.5	-0.37	0.12	-0.75	-0.255	0.25	-0.5	0
	0	-0.5	-0.25	0	-0.25	-0.125	-0.12	-0.25	-0.245	0	-0.5	-0.25	0.25	-1.25	-0.375	-0.12	-0.37	-0.305	0.12	-0.87	-0.315	0	-0.25	-0.125
	0.12	-0.75	-0.255	-0.12	0	-0.12	-0.25	0	-0.25	-0.12	-0.25	-0.245	0.5	-1.5	-0.25	-0.12	-0.37	-0.305	0.12	-0.62	-0.19	0	-0.25	-0.125
MEAN	-0.032	-0.548	-0.306	-0.052	-0.331	-0.217	-0.092	-0.279	-0.231	-0.040	-0.384	-0.232	0.134	-0.738	-0.235	0.013	-0.393	-0.184	0.028	-0.508	-0.225	0.134	-0.436	-0.084
SD	0.182	0.203	0.185	0.122	0.227	0.175	0.168	0.188	0.112	0.059	0.187	0.070	0.396	0.567	0.218	0.161	0.178	0.249	0.151	0.257	0.147	0.135	0.135	0.081

Subject	pair 2 tail t-test to determine if there is any difference in accommodation when one eye has no negative sphere.											
sphere	-0.25	-0.5	-0.75	-1	-1.25	-1.5	-1.75	-2	-2.25	-2.5	-2.75	-3
p value	0.014	0.009	0.811	0.325	0.000	0.336	0.367	0.041	0.344	0.004	0.665	0.559
sphere	-3.25	-3.5	-3.75	-4	-4.25	-4.5	-5	-5.5	-6	-6.5	-7	
p value	0.213	0.345	0.089	0.033	0.886	0.344	0.240	0.540	0.636	0.488	0.004	

	Negative spheres which stimulated a significant change in accommodation.(OS)									
	-0.25	-0.5	-1.25	-2	-2.5	-4	-7			
Significant change in accommodation	0.096	0.143	0.180	0.097	0.098	0.113	0.110			

SUBJECT: N
AGE 26 YEARS
PRESC RE -2.00DS VA 6/5
LE -2.25DS VA 6/5
AMP. OF ACCOMMODATION: 8.00D
NOTE: THE SUBJECT WAS WEARING CONTACT LENS CORRECTION DURING THE EXPERIMENT. SUBJECT IS RI RE IS UNDERCORRECT BY -0.50DS.

	0			-0.25			-0.5			-0.75			-1			-1.25			-1.5			-1.75		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0.37	-1.25	-0.255	0.37	-1.37	-0.315	0.37	-1.25	-0.255	0.25	-0.75	-0.125	0.12	-1.12	-0.44	0.12	-1.12	-0.44	-0.25	-1	-0.75	0.37	-1.37	-0.315
	0.37	-1.37	-0.315	0.37	-1	-0.13	0.37	-0.87	-0.065	0.25	-0.87	-0.185	0	-0.87	-0.435	0	-1	-0.5	-0.12	-1.25	-0.745	0.25	-1.25	-0.375
	0.37	-1.12	-0.19	0.37	-1.12	-0.19	0.25	-0.87	-0.185	0.37	-1	-0.13	0.25	-1	-0.25	0	-1.25	-0.625	-0.25	-1	-0.75	0.37	-1.25	-0.255
	0.5	-1.25	-0.125	0.37	-1.12	-0.19	0.25	-0.75	-0.125	0.37	-1.25	-0.255	0.12	-1	-0.38	0	-1.12	-0.56	-0.12	-1.12	-0.68	0.25	-1.25	-0.375
	0.37	-1.12	-0.19	0.37	-0.87	-0.065	0.12	-0.62	-0.19	0.25	-1	-0.25	0.12	-1	-0.38	0	-1.25	-0.625	-0.37	-1	-0.87	0.25	-1.37	-0.435
	0.37	-1.12	-0.19	0.37	-1	-0.13	0.37	-0.87	-0.065	0.25	-0.87	-0.185	0.25	-1	-0.25	0	-1.37	-0.685	-0.25	-1.12	-0.81	0.25	-1.25	-0.375
	0.12	-1.25	-0.505	0.5	-1.12	-0.06	0.12	-0.87	-0.315	0.37	-1.25	-0.255	0.12	-0.87	-0.315	0	-1.5	-0.75	-0.37	-1.25	-0.995	0.12	-0.87	-0.315
	0.37	-1.12	-0.19	0.5	-1.75	-0.375	0.25	-1.12	-0.31	0.37	-1.37	-0.315	0.25	-1	-0.25	-0.5	-1.37	-1.185	-0.25	-1	-0.75	0	-1.12	-0.56
	0.25	-1.25	-0.375	0.37	-1.12	-0.19	0.25	-1	-0.25	0.25	-1.37	-0.435	0.25	-1	-0.25	-0.37	-1.12	-0.93	-0.25	-0.87	-0.685	0.25	-1.12	-0.31
	0.37	-1.37	-0.315	0.37	-1	-0.13	0.12	-0.87	-0.315	0.25	-0.75	-0.125	0.25	-1	-0.38	0.25	-1.5	-0.5	-0.37	-1.25	-0.995	0.37	-1	-0.13
	0.25	-1.12	-0.31	0.37	-0.75	-0.005	0.25	-0.87	-0.185	0.5	-1.12	-0.06	0.25	-1	-0.25	-0.25	-1.25	-0.875	0	-0.87	-0.435	0.12	-1	-0.38
	0.5	-1.25	-0.125	0.37	-0.75	-0.005	0.25	-0.75	-0.125	0.37	-0.75	-0.005	0.12	-1	-0.38	0	-1.62	-0.81	-0.37	-1.12	-0.93	0.25	-0.87	-0.185
MEAN	0.351	-1.216	-0.257	0.392	-1.081	-0.148	0.248	-0.893	-0.188	0.321	-1.029	-0.194	0.164	-0.988	-0.330	-0.083	-1.269	-0.707	-0.248	-1.071	-0.783	0.238	-1.143	-0.334
SD	0.105	0.085	0.112	0.051	0.273	0.113	0.082	0.168	0.082	0.087	0.238	0.117	0.083	0.065	0.077	0.209	0.187	0.218	0.118	0.136	0.155	0.112	0.178	0.113

	-2			-2.25			-2.5			-2.75			-3			-3.25			-3.5			-3.75		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0.37	-1.25	-0.255	0.37	-1	-0.13	0.12	-0.87	-0.315	0.37	-1	-0.13	0.37	-1.25	-0.255	0.5	-1.12	-0.06	0.25	-1	-0.25	0.37	-1.12	-0.19
	0.25	-0.87	-0.185	0.37	-1.25	-0.255	0.12	-0.75	-0.255	0.5	-1.25	-0.125	0.37		-0.13	0.37	-1.25	-0.255	0.37	-1.12	-0.19	0.37	-1.12	-0.19
	0.25	-0.87	-0.185	0.37	-1.12	-0.19	0.25	-0.87	-0.185	0.37	-1	-0.13	0.25	-0.75	-0.125	0.25	-1.12	-0.31	0.25	-1.5	-0.5	0.25	-0.87	-0.185
	0.37	-1	-0.13	0.37	-1.25	-0.255	0.12	-0.87	-0.315	0.37	-1.12	-0.19	0.37	-1	-0.13	0.37	-1.12	-0.19	0.37	-1.25	-0.255	0.25	-0.75	-0.125
	0.25	-1	-0.25	0.25	-1.25	-0.375	0.12	-0.87	-0.315	0.37	-1.12	-0.19	0.25	-0.87	-0.185	0.5	-1.25	-0.125	0.37	-1.37	-0.315	0.25	-1	-0.25
	0.37	-1	-0.13	0.25	-1.25	-0.375	0.25	-0.87	-0.185	0.25	-0.87	-0.185	0.12	-1	-0.38	0.25	-1.25	-0.375	0.37	-1.62	-0.44	0.12	-1	-0.38
	0.37	-1.12	-0.19	0.37	-1.25	-0.255	0.25	-0.87	-0.185	0.12	-1	-0.38	0.25	-1	-0.25	0.37	-1.25	-0.255	0.62	-1	0.12	0.12	-1	-0.38
	0.25	-1	-0.25	0.37	-1	-0.13	0.12	-0.87	-0.315	0.25	-0.87	-0.185	0.25	-1	-0.25	0.5	-1.37	-0.185	0.37	-1	-0.13	0.12	-1	-0.38
	0.37	-1.25	-0.255	0.37	-0.87	-0.065	0.25	-0.87	-0.185	0.37	-0.87	-0.065	0.25	-1.12	-0.31	0.37	-1.12	-0.19	0.37	-1	-0.13	0.25	-1	-0.25
	0.37	-1.25	-0.255	0.37	-1.12	-0.19	0.12	-0.87	-0.315	0.37	-1	-0.13	0.25	-1	-0.25	0.25	-1.12	-0.31	0.37	-1.12	-0.19	0.12	-1	-0.38
	0.25	-1	-0.25	0.37	-1	-0.13	0.12	-0.87	-0.315	0.25	-1	-0.25	0.37	-1	-0.13	0.37	-1.37	-0.315	0.37	-1.12	-0.19	0.37	-0.87	-0.065
	0.25	-0.87	-0.185	0.25	-1.12	-0.31	0.12	-0.87	-0.315	0.37	-0.87	-0.065	0.25	-0.87	-0.185	0.25	-1.5	-0.5	0.37	-1.25	-0.255	0.37	-1.12	-0.19
MEAN	0.310	-1.040	-0.210	0.340	-1.123	-0.222	0.163	-0.871	-0.272	0.330	-0.998	-0.169	0.279	-0.988	-0.215	0.363	-1.237	-0.256	0.371	-1.196	-0.227	0.247	-1.000	-0.247
SD	0.063	0.148	0.136	0.054	0.131	0.100	0.064	0.053	0.058	0.097	0.120	0.088	0.076	0.125	0.082	0.098	0.126	0.118	0.081	0.209	0.158	0.107	0.112	0.110

	-4			-4.25			-4.5			-4.75			-5			-5.5			-6			-6.5		
	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP	SPHERE	CYL	EQ SP
	0.37	-1.12	-0.19	0.37	-1.12	-0.19	0.37	-1.12	-0.19	0.25	-1	-0.25	0.37	-0.87	-0.065	0	-0.87	-0.435	0.25	-0.87	-0.185	0.37	-0.75	-0.005
	0.5	-1.12	-0.06	0.37	-1	-0.13	0.37	-1.12	-0.19	0.25	-1.25	-0.375	0.25	-1.12	-0.31	0.25	-1.25	-0.375	0.37	-1	-0.13	0.25	-1	-0.25
	0.37	-1.12	-0.19	0.37	-0.87	-0.065	0.37	-1.12	-0.19	0.25	-1	-0.25	0.37	-0.62	0.06	0.37	-1.25	-0.255	0.25	-1	-0.25	0.37	-1	-0.13
	0.5	-1.12	-0.06	0.37	-1	-0.13	0.37	-1.12	-0.19	0.25	-1	-0.25	0.37	-0.87	-0.065	0.37	-1.25	-0.255	0.37	-1.12	-0.19	0.25	-0.75	-0.125
	0.37	-1.12	-0.19	0.37	-0.75	-0.005	0.37	-1	-0.13	0.25	-1.25	-0.375	0.37	-0.87	-0.065	0.37	-1.25	-0.255	0.37	-1	-0.13	0.25	-0.75	-0.125
	0.37	-0.87	-0.065	0.37	-1.12	-0.19	0.25	-1	-0.25	0.37	-1.12	-0.19	0.37	-1	-0.13	0.5	-1.37	-0.185	0.5	-1.25	-0.125	0.12	-1	-0.38
	0.25	-0.75	-0.125	0.25	-1	-0.25	0.25	-1	-0.25	0.25	-1.12	-0.31	0.37	-0.87	-0.065	0.37	-1.5	-0.38	0.37	-1	-0.13	0.25	-1.12	-0.31
	0.37	-1	-0.13	0.37	-1.12	-0.19	0.37	-1.12	-0.19	0.25	-1	-0.25	0.25	-0.87	-0.185	0.37	-1.25	-0.255	0.37	-1.25	-0.255	0.26	-1.12	-0.31
	0.37	-1	-0.13	0.37	-1.12	-0.19	0.25	-1	-0.25	0.25	-1.25	-0.375	0.37	-1	-0.13	0.37	-1.37	-0.315	0.37	-1.12	-0.19	0.37	-0.87	-0.065
	0.37	-0.87	-0.065	0.5	-1.12	-0.06	0.37	-1	-0.13	0.37	-1.25	-0.255	0.37	-0.87	-0.065	0.62	-1.87	-0.315	0.25	-1	-0.25	0.25	-0.87	-0.185
	0.25	-1.12	-0.31	0.5	-1	0	0.37	-1.12	-0.19	0.37	-1.25	-0.255	0.37	-1	-0.13	0.37	-1.12	-0.19	0.37	-1	-0.13	0.25	-0.87	-0.185
	0.25	-1.12	-0.31	0.25	-1.12	-0.31	0.37	-1	-0.13	0.37	-1.25	-0.255	0.25	-1	-0.25	0.25	-1	-0.25	0.37	-0.75	-0.005	0.37	-1.12	-0.19
MEAN	0.382	-1.028	-0.152	0.372	-1.028	-0.143	0.340	-1.060	-0.180	0.290	-1.145	-0.283	0.340	-0.913	-0.117	0.351	-1.279	-0.289	0.351	-1.030	-0.164	0.279	-0.935	-0.188
SD	0.083	0.131	0.088	0.075	0.118	0.095	0.054	0.063	0.044	0.058	0.117	0.081	0.054	0.124	0.088	0.148	0.250	0.273	0.071	0.142	0.072	0.076	0.145	0.109

	-7		
	SPHERE	CYL	EQ SP
	0.37	-1.37	-0.315
	0.37	-1.12	-0.19
	0.25	-0.87	-0.185
	0.37	-1	-0.13
	0.37	-0.87	-0.065
	0.25	-1.37	-0.435
	0.37	-1.12	-0.19
	0.37	-1	-0.13
	0.37	-1.12	-0.19
	0.37	-1	-0.13
	0.37	-1	-0.13
	0.25	-0.87	-0.185
MEAN	0.340	-1.059	-0.180
SD	0.054	0.172	0.098

Subject	pair 2 tail t-test to determine if there is any difference in accommodation when one eye has no negative sphere.											
sphere	-0.25	-0.5	-0.75	-1	-1.25	-1.5	-1.75	-2	-2.25	-2.5	-2.75	-3
p value	0.053	0.078	0.136	0.100	0.000	0.000	0.144	0.155	0.496	0.724	0.013	0.761
sphere	-3.25	-3.5	-3.75	-4	-4.25	-4.5	-4.75	-5	-5.5	-6	-6.5	-7
p value	0.881	0.866	0.799	0.028	0.018	0.038	0.407	0.008	0.281	0.028	0.135	0.147

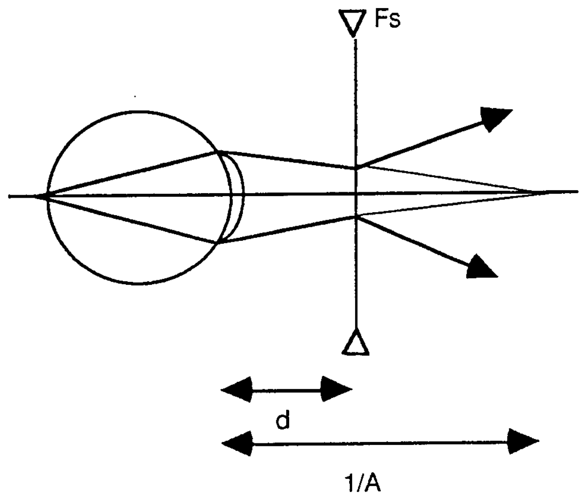
	Negative spheres which stimulated a significant change in accommodation.(OS)									
	-1	-1.25	-1.5	-2.75	-4	-4.25	-5	-6		
Significant change in accommodation	0.073	0.450	0.528	-0.047	-0.105	-0.115	-0.140	-0.093		

SUBJECT: RD
AGE 20 YEARS
PRESC: RE -4.50DS -1.25DC ×90 VA 6/6
LE -4.25DS -0.75DC VA 6/6
AMP. OF ACCOMMODATION: 11.50D
NOTE: THE SUBJECT WAS WEARING RGP CORRECTION DURING THE EXPERIMENT. A -4.50DS WAS REQUIRED ON THE LE TO ENABLE HIM TO SEE 6/6 LINE. ACCOMMODATION WAS STIMULATED ON LE AND MEASUREMENT ON RE.

SUBJECT: AW
AGE 19 YEARS
PRESC: RE -4.25DS VA 6/6
LE Plano VA 6/6
AMP. OF ACCOMMODATION: 11.50

Deriavation of formula.

We suppose that the eye is initially emmetropic and accommodates by +A dioptres (refered to cornea).



Starting at retina

The distance of conjugate point from cornea = 1/A

The distance of conjugate point from lens = (1/A) - d = (1-Ad)/A

= (1-Ad)/A

Ie. Vergence of light reaching lens = A/(1 - Ad)

Vergence of light leaving lens = A/(1-Ad) + Fs

Now this vergence is what the autorefractor measures but if the vergence was positive it would decide that the eye was myopic and needed a negative correction. Thus the autorefractor gives a reversed sign or

A/((1-Ad) + Fs = - R

ie. A + Fs - FsAd = _R + RAd

or A -FsAd - RAd = -R-Fs

or A [1-d(Fs + R)] = -(Fs + R)

or **A = -(Fs + R)/[1 - d(Fs + R)]**

Appendix 6.1

Name	Age	Amplitude of Accommodation (D)	Stereoacuity (sec or arc)	Near phoria	Refractive error
D	21	11	60	1 exo	Nil
P	19	11	240	6 exo	RE -2.25DS L-0.50DS
S	29	10	60	ortho.	RE -2.75DS LE -3.25DS
C	19	12	30	3 exo	RE -3.75DS -0.50DC x 115 LE -2.25DS
R	21	12	30	5 eso	RE -5.50DS -0.50DC x 172 LE -5.25DS -0.25DC x 10
H	27	8	60	1 eso	Nil
SP	24	9.5	30	ortho.	Nil
DB	20	9	30	ortho.	Nil
M B	25 19	9.5 11	60 60	2 exo. 1 exo.	Nil RE -1.00DS LE -1.00DS
V	24	9.5	60	2 exo.	RE -1.00DS LE 0.75DS
MH	21	10	15	2 exo	Nil
AS	22	8	240	ortho	RE -0.25DS -0.25DC x 90 LE PL
AC	19	12	60	1 exo.	RE -3.50DS LE -3.50DS
AB	26	9	60	ortho.	NIL
N	26	9	60	2 exo.	RE -2.25DS LE -2.00DS
RF	18	11	120	6 exo.	RE -5.25DS -0.75DC x 170 LE -5.00DS -1.50DC x 20
RN	22	11	60	ortho.	RE +0.50DS LE +0.50DS
RS	20	14	60	1 exo.	RE -5.25DS -1.25DC x 190 LE -5.50DS -0.75DC x 172

Appendix 6.2

Subject: D

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff. Sph.	Sphere	Cyl	Eff. Sph.
	2.37	0.87	2.81	1.87	1	2.37
	2.25	0.87	2.69	1.87	0.62	2.18
	2	0.87	2.44	1.87	0.75	2.25
	2.12	1	2.62	1.62	1	2.12
	2.12	1	2.62	1.75	0.87	2.19
	2.12	0.87	2.56	1.62	0.87	2.06
	2.5	1	3	1.5	0.87	1.94
	2.62	0.87	3.06	1.5	0.87	1.94
	2.12	1	2.62	1.62	1	2.12
	2	1	2.5	1.62	0.87	2.06
	2.12	0.75	2.5	1.5	0.87	1.94
	2	0.75	2.38	1.5	1	2
	2	0.75	2.38	1.62	1	2.12
Average	2.180	0.890	2.630	1.650	0.890	2.100
S.D.	0.200	0.200	0.100	0.140	0.110	0.130

Subject: P

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff. Sph.	Sphere	Cyl	Eff. Sph.
	2	0.5	2.25	1.75	0.37	1.94
	2	0.5	2.25	1.62	0.37	1.81
	1.87	0.37	2.06	1.75	0.37	1.94
	1.87	0.5	2.12	1.62	0.37	1.81
	1.75	0.37	1.94	1.62	0.37	1.81
	2	0.5	2.25	1.62	0.37	1.81
	2	0.37	2.19	1.5	0.5	1.75
	1.87	0.62	2.18	1.5	0.62	1.81
	1.75	0.5	1.94	1.37	0.75	1.75
	1.5	0.5	1.75	1.62	0.37	1.81
	1.5	0.62	1.81	1.25	0.62	1.56
	2.12	0.25	2.25	1.25	0.62	1.56
	1.62	0.37	1.81	1.25	0.75	1.63
	1.75	0.37	1.94	1.5	0.62	1.81
	1.75	0.37	1.94	1.37	0.62	1.68
	1.62	0.5	1.87	1.5	0.62	1.81
	1.87	0.37	2.06	1.62	0.62	1.93
Average	1.810	0.450	2.040	1.510	0.530	1.780
S.D.	0.180	0.100	0.170	0.160	0.140	0.110

Subject: S

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff. Sph.	Sphere	Cyl	Eff. Sph.
	1.37	1	1.87	1.62	0.62	1.93
	1.62	0.87	2.06	1.62	0.75	2
	1.87	1.12	2.43	1.25	0.75	1.63
	1.87	0.37	2.06	1.12	0.75	1.5
	1.75	0.62	2.06	0.87	0.87	1.31
	1.75	0.75	2.13	0.37	1	0.87
	1.5	1	2	1.75	0.87	2.19
	1.25	1	1.75	1.37	1.25	2
	1.5	0.5	1.75	1.75	0.75	2.13
	1.87	0.5	2.12	1.62	0.75	2
	1.25	1.12	1.81	1.75	0.87	2.19
	1.62	1.37	2.31	2.25	0.87	2.69
	1.25	0.87	1.69	1.87	1	2.37
Average	1.580	0.850	2.500	1.480	0.850	1.910
S.D.	0.240	0.290	0.220	0.490	0.160	0.480

Subject: C

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff Sph	Sphere	Cyl	Eff. Sph
	1.5	1.5	2.25	1.87	1.37	2.56
	1.37	1.37	2.06	2.25	1.5	3
	1.25	1.25	1.88	1.62	1.5	2.37
	1.5	1.37	2.19	1.5	1.5	2.25
	1.25	1.5	2	1.75	1.5	2.5
	1	1.5	1.75	2	1.37	2.69
	1.25	1.37	1.94	1.87	1.5	2.62
	1.25	1.5	2	1.75	1.5	2.5
	1.5	2.37	2.69	1.87	1.37	2.56
	1.12	1.5	1.87	2	1.37	2.69
	1.37	1.37	2.06	1.5	1.5	2.25
	1.37	1.62	2.18	1.62	1.5	2.37
	2	1	2.5	1.87	1.12	2.43
	1.37	1.37	2.06	2.12	1.37	2.81
	1.12	1.62	1.93	1.62	1.37	2.31
	1.37	2.37	2.56	1.37	1.5	2.12
Average	1.350	1.540	2.120	1.790	1.430	2.500
S.D.	0.230	0.360	0.260	0.240	0.100	0.230

Subject: R

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff Sph	Sphere	Cyl	Eff. Sph
	2	0.25	2.13	1.62	0.62	1.93
	2.25	0.25	2.38	1.75	0.5	2
	1.87	0	1.87	1.75	0.25	1.88
	2	0.25	2.13	1.37	0.37	1.56
	1.62	0.25	1.75	1.37	0.5	1.62
	1.25	0.25	1.38	1.12	0.62	1.43
	2.12	0.25	2.25	1.37	0.5	1.62
	1.5	0.37	1.69	1.75	0.25	1.88
	1.62	0.5	1.87	1	0.25	1.125
	1.37	0.62	1.68	0.87	0.25	1
	1.87	0.5	2.12	2	0.37	2.19
	1.62	0.5	1.87	1.75	0.25	1.88
	1.87	0.25	2	1.62	0.62	1.93
	1.87	0	1.87	1.62	0.5	1.87
	1.37	0.75	1.75	1.5	0.37	1.69
	2	0.37	2.19	1.75	0.62	2.06
Average	1.760	0.340	1.930	1.510	0.430	1.730
S.D.	0.290	0.200	0.260	0.310	0.150	0.330

Subject: H

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff Sph	Sphere	Cyl	Eff. Sph
	1.75	0.75	2.13	1.62	0.87	2.06
	1.25	1	1.75	1.62	0.87	2.06
	1.75	1	2.25	1.75	0.75	2.13
	1.62	0.87	2.06	1.87	0.87	2.31
	1.87	0.87	2.31	1.12	1.37	1.81
	1.87	0.75	2.25	0.75	1	1.25
	1.75	1	2.25	1.12	1.37	1.81
	2.37	0.5	2.62	0.87	1.75	1.75
	1.75	0.75	2.13	1.62	1.12	2.18
	1.87	0.75	2.25	1.62	1	2.12
	1.87	0.5	2.12	1.12	1	1.62
	1.5	0.75	1.88	1.37	0.87	1.81
	2	0.62	2.31	1.25	0.75	1.63
	1.87	0.62	2.18	1.5	0.87	1.94
	1.5	1	2	1.5	0.75	1.88
	1.87	1.25	2.5	1.25	0.75	1.63
	1.87	0.75	2.25	1.37	0.87	1.81
	1.37	1	1.87	1.5	0.75	1.88
Average	1.760	0.820	2.170	1.380	0.980	1.870
S.D.	0.250	0.200	0.210	0.300	0.270	0.250

Subject: SP

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff Sph	Sphere	Cyl	Eff. Sph
	2.12	0	2.12	1.75	0.5	2
	2	0.5	2.25	1.75	0.37	1.94
	1.87	0.37	2.06	1.87	0.37	2.06
	2	0.37	2.19	1.87	0.5	2.12
	1.87	0.37	2.06	1.62	0.37	1.81
	1.75	0.37	1.94	1.62	0.5	1.87
	1.87	0.37	2.06	1.75	0.37	1.94
	2	0.37	2.19	1.75	0.37	1.94
	1.87	0.5	2.12	1.75	0.37	1.94
	1.87	0.5	2.12	1.87	0.37	2.06
	1.87	0.25	2	1.75	0.37	1.94
	1.87	0.37	2.06	1.75	0.37	1.94
	1.75	0.5	2	1.75	0.5	2
	1.75	0.62	2.06	1.87	0.37	2.06
	2.12	0.37	2.31	1.75	1.25	2.38
	2.12	0.37	2.31	1.87	0.37	2.06
	2.12	0.25	2.25	2	0.5	2.25
	1.87	0.25	2	1.62	0.87	2.06
	2	0.37	2.19	2.12	0.25	2.25
	1.87	0.37	2.06	2.12	0.37	2.31
	1.87	0.37	2.06	1.87	0.37	2.06
Average	1.930	0.370	2.110	1.810	0.460	2.040
S.D.	0.120	0.130	0.110	0.140	0.220	0.150

Subject: DB

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff Sph	Sphere	Cyl	Eff. Sph
	2.5	0.75	2.88	2.25	1.12	2.81
	1.5	0.62	1.81	2.12	0.75	2.5
	2	0.62	2.31	1.5	1.25	2.13
	1.5	0.5	1.75	1.62	1.25	2.25
	2.12	1.37	2.81	2.25	1	2.75
	1.87	1.5	2.62	1.25	1	1.75
	1.62	1.62	2.43	2.12	0.75	2.5
	1.87	1.37	2.56	1.75	1	2.25
	1.75	0.87	2.19	2.25	1	2.75
	1.75	1	2.25	1.62	0.87	2.06
	1.37	1	1.87	1.5	0.87	1.94
	1.37	1.37	2.06	1.5	1.25	2.13
	1.37	1.12	1.93	1.62	0.75	2
	1.37	1	1.87	1.5	0.87	1.94
	1.62	1.12	2.18	1.62	1	2.12
	1	0.62	1.31	1.87	1	2.37
	1.37	1.37	2.06	1.62	0.5	1.87
	2	2.25	3.13	1.62	0.5	1.87
Average	1.660	1.120	2.220	1.750	0.930	2.220
S.D.	0.360	0.440	0.460	0.310	0.220	0.330

Subject: M

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff Sph	Sphere	Cyl	Eff. Sph.
	1.12	1.75	2	1.75	0.87	2.19
	1.12	1.37	1.81	1.5	1.25	2.13
	1.62	1.25	2.25	1.62	0.62	1.93
	1.62	0.75	2	1.37	1.25	2
	1.5	0.75	1.88	1.37	1	1.87
	1.5	0.75	1.88	1.5	1.12	2.06
	1.75	0.75	2.13	1.37	1.5	2.12
	1.75	0.87	2.19	1.37	2	2.37
	1.62	0.75	2	1.12	1.5	1.87
	1.62	0.87	2.06	1.12	1.87	2.06
	1.5	0.75	1.88	1.37	1	1.87
	1.37	0.87	1.81	1.5	1.12	2.06
	1.37	0.75	1.75	1.25	1.75	2.13
	1.37	0.87	1.81	1.12	1.87	2.06
Average	1.490	0.940	1.960	1.380	1.340	2.050
S.D.	0.200	0.310	0.160	0.190	0.420	0.140

Subject: B

	Crossed Disparity			Zero Disparity		
	Sphere	Cyl	Eff. Sph.	Sphere	Cyl	Eff. Sph.
	1.75	1	2.25	1.62	1	2.12
	1.87	0.87	2.31	1.5	1.12	2.06
	1.62	1	2.12	1.5	0.87	1.94
	1.75	0.75	2.13	1.75	0.62	2.06
	2	0.75	2.38	1.75	0.87	2.19
	1.62	1	2.12	1.5	1.12	2.06
	1.62	0.87	2.06	1.62	1	2.12
	1.75	0.87	2.19	1.75	0.87	2.19
	1.75	0.75	2.13	2	0.75	2.38
	1.87	0.87	2.31	1.75	0.75	2.13
	1.75	1	2.25	1.75	0.754	2.13
	1.75	1.12	2.31	1.62	0.87	2.06
	1.75	1	2.25	1.5	1	2
	2	0.75	2.38	1.87	0.87	2.31
Average	1.780	0.900	2.230	1.677	0.890	2.125
S.D.	0.120	0.120	0.100	0.150	0.150	0.120

Subjec V

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity Image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	1	1.37	1.685	1.37	0.75	1.745	1.5	1.12	2.06
	1	1.25	1.625	1.12	0.75	1.495	1.12	1.25	1.745
	1.25	1.37	1.935	1.12	1	1.62	1	1	1.5
	1.12	1.62	1.93	1	1	1.5	1.25	1.5	2
	1	1.37	1.685	1	1	1.5	0.87	1.25	1.495
	1	1.5	1.75	1.12	0.87	1.555	0.87	1.5	1.62
	1.12	1.25	1.745	1.12	1	1.62	1.12	1.12	1.68
	1	1.62	1.81	1	1	1.5	0.75	1.5	1.5
	1.12	1.25	1.745	0.87	1.12	1.43	0.62	1.25	1.245
	1	1.37	1.685	0.75	1.12	1.31	1.25	1.37	1.935
	1	1.25	1.625	0.87	1.12	1.43	1	1	1.5
	1.12	1.37	1.805	0.75	1.25	1.375	0.87	1.37	1.555
	1	1.37	1.685	0.75	1.25	1.375	0.75	1.25	1.375
	1	1.25	1.625	1	1.12	1.56	1	1.37	1.685
	1.12	1.37	1.805	0.87	1.12	1.43	0.87	1.25	1.495
	1.12	1.37	1.805	1	1	1.5	1	1.25	1.625
	1	1.25	1.625	1.12	0.87	1.555	0.87	1.12	1.43
	1	1.62	1.81	1.12	1	1.62	0.75	1.25	1.375
	1	1.5	1.75	1	1.25	1.625	0.87	1.12	1.43
Average	1.051	1.385	1.744	0.997	1.031	1.513	0.965	1.255	1.592
S.D.	0.074	0.130	0.095	0.160	0.149	0.107	0.213	0.153	0.218

Subject: N

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity Image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	1.25	0.75	1.625	0.87	0.62	1.18	1.37	1.25	1.995
	1.25	0.75	1.625	1	0.62	1.31	0.62	1.25	1.245
	1.37	0.75	1.745	1.25	0.62	1.56	1.37	1.37	2.055
	1.12	1	1.62	0.87	0.75	1.245	2.37	1.25	2.995
	1	0.87	1.435	0.75	0.75	1.125	1.5	0.75	1.875
	1.12	1	1.62	1	0.5	1.25	1.25	1.12	1.81
	1	1.12	1.56	1	0.5	1.25	1.25	1.25	1.875
	1.12	1	1.62	1	0.62	1.31	0.87	1.12	1.43
	0.87	1.12	1.43	0.87	0.62	1.18	0.5	1.37	1.185
	1.12	1.25	1.745	0.87	0.75	1.245	1.37	0.87	1.805
	1	1.12	1.56	1	0.62	1.31	1.5	1.12	2.06
	1.25	1	1.75	1	0.62	1.31	1.37	0.75	1.745
	1.25	1	1.75	0.62	0.5	0.87	1.25	1.37	1.935
	1.12	0.87	1.555	1	0.37	1.185	1.25	1.37	1.935
	1.25	0.87	1.685	1.12	0	1.12	1.87	1	2.37
	1.25	0.87	1.685	1.12	0.87	1.555	1.25	1.12	1.81
	1.25	0.87	1.685	0.62	0.87	1.055	1.37	0.87	1.81
	1.25	1	1.75	1.12	0.75	1.495	1.37	0.62	1.68
	1.12	1	1.62	1	0.62	1.31	1.62	1.25	2.245
Average	1.156	0.958	1.635	0.952	0.609	1.256	1.333	1.109	1.887
S.D.	0.125	0.138	0.098	0.163	0.194	0.166	0.406	0.235	0.399

Subject: RF

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity Image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	1.12	1	1.62	1.37	1.25	1.995	1	1.12	1.56
	0.87	1.37	1.555	1.75	0.87	2.185	1.62	0.37	1.805
	1	1.25	1.625	1	0.87	1.435	1.25	1	1.75
	1.5	1.12	2.06	1.25	0.87	1.685	1.12	1	1.62
	1.25	1.62	2.06	1.5	1	2	1.25	0.87	1.685
	2	0.62	2.31	1.25	1.12	1.81	1.5	0.37	1.685
	0.87	1.37	1.555	1	1.12	1.56	1.5	0.87	1.935
	1	1.37	1.685	1.37	1.12	1.93	0.87	1	1.37
	1.12	1.25	1.745	1.12	1.12	1.68	0.62	1.37	1.305
	1.37	1.37	2.055	1.37	1	1.87	1.37	0.5	1.62
	1.5	1.37	2.185	1.12	1	1.62	1	0.87	1.435
	1.12	1.62	1.93	1.12	1	1.62	0.75	1.37	1.435
	1.12	1.37	1.805	0.75	1	1.25	2	0.25	2.125
	1	1.62	1.81	0.75	0.75	1.125	1	0.5	1.25
	1.5	1.37	2.185	1.5	0.75	1.875	1.25	0.5	1.5
Average	1.223	1.313	1.879	1.215	0.989	1.709	1.207	0.797	1.605
S.D.	0.304	0.258	0.251	0.277	0.145	0.289	0.359	0.361	0.238

Subjec MH

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity Image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	1.5	1.25	2.125	1.12	-0.87	0.685	2.12	0.5	2.37
	1.75	0.75	2.125	1.62	-0.62	1.31	2.25	0.25	2.375
	1.62	0.75	1.995	1.25	-0.62	0.94	2.12	0.37	2.305
	1.37	0.87	1.805	1.62	0.5	1.87	1.5	0.75	1.875
	1.5	0.87	1.935	1.75	0.25	1.875	2	0.5	2.25
	1.62	0.75	1.995	1.37	0.25	1.495	1.75	0.75	2.125
	1.5	1	2	1.25	0.62	1.56	1.75	0.87	2.185
	1.75	1	2.25	1.37	0.5	1.62	1.62	1	2.12
	1.5	0.87	1.935	1.62	0.37	1.805	1.62		2.12
	1.62	1.12	2.18	1.5	0.25	1.625	1.5	0.87	1.935
	1.62	1	2.12	1.75	0.37	1.935	1.87	1	2.37
	1.75	1.12	2.31	1.37	0.5	1.62	1.62	0.87	2.055
	1.62	1	2.12	1.62	0.37	1.805	1.75	0.87	2.185
	1.62	0.75	1.995	1.5	0.5	1.75	1.87	0.87	2.305
	1.62	0.75	1.995	1.87	0	1.87	1.5	1	2
	1.62	0.62	1.93	1.62	0.5	1.87	1.87	0.62	2.18
	1.62	0.75	1.995	1.87	0.75	2.245	2	0.75	2.375
	1.75	0.87	2.185	2.12	0.37	2.305	1.87	0.75	2.245
	2	1	2.5	1.87	0.5	2.12	1.5	0.87	1.935
	1.62	0.87	2.055	1.87	0.5	2.12	1.37	0.87	1.805
Average	1.629	0.898	2.078	1.597	0.250	1.721	1.773	0.767	2.156
S.D.	0.132	0.160	0.157	0.258	0.442	0.400	0.245	0.215	0.176

Subject: RN

	Crossed Disparit image			Uncrossed Disparity Image			Zero Disparity Image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	1.87	0.5	2.12	1.75	0.5	2	2	0.62	2.31
	2	0.5	2.25	1.75	0.5	2	2.37	0.37	2.555
	2.12	0.5	2.37	1.87	0.25	1.995	1.87	0.62	2.18
	2	0.5	2.25	1.75	0.5	2	2.12	0.37	2.305
	2.25	0.37	2.435	2	0.25	2.125	1.75	0.25	1.875
	1.87	0.37	2.055	2	0.25	2.125	1.87	0.37	2.055
	2	0.37	2.185	2.12	0	2.12	1.87	0.62	2.18
	1.5	1.25	2.125	1.87	0.37	2.055	1.75	0.37	1.935
	1.75	0.5	2	1.87	0.75	2.245	2	0.25	2.125
	1.87	0.5	2.12	1.62	0.62	1.93	2.12	0.5	2.37
	2.12	0.37	2.305	1.12	1.12	1.68	1.37	0.75	1.745
	1.75	0.75	2.125	1.75	0.5	2	1.75	0.62	2.06
	2.25	0.5	2.5	2	0	2	1.75	0.37	1.935
	1.87	0.37	2.055	1.87	0	1.87	1.87	0.5	2.12
	2	0.37	2.185	1.62	0.37	1.805	1.5	1.12	2.06
	1.87	0.37	2.055	1.87	0.5	2.12	1.5	0.62	1.81
	1.5	0.75	1.875	1.75	0.25	1.875	1.62	0.5	1.87
Average	1.917	0.520	2.177	1.799	0.396	1.997	1.826	0.519	2.088
S.D.	0.216	0.223	0.161	0.222	0.286	0.137	0.253	0.212	0.217

Subjec AB

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity Image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	1.62	1.12	2.18	1.62	0.75	1.995	1.62	0.25	1.745
	1.62	0.87	2.055	1.75	0.75	2.125	1.12	0.87	1.555
	1.37	1	1.87	1.62	0.75	1.995	1.62	0.62	1.93
	1.62	0.87	2.055	1.62	0.62	1.93	1.5	0.37	1.685
	1.62	0.75	1.995	1.37	0.75	1.745	1.62	0.62	1.93
	2.12	1.12	2.68	1.5	0.75	1.875	1.62	1	2.12
	1.62	0.87	2.055	1.37	0.87	1.805	1.37	1	1.87
	1.5	0.87	1.935	1.37	0.75	1.745	1.62	1.12	2.18
	0.87	1.75	1.745	1.62	0.75	1.995	1.37	0.75	1.745
	1.25	1	1.75	1.5	0.87	1.935	1.25	0.75	1.625
	1.12	0.87	1.555	1.5	0.62	1.81	1.62	0.75	1.995
	1.25	0.75	1.625	1.5	1	2	1.5	0.62	1.81
	1.5	0.62	1.81	1.37	0.75	1.745	1.5	0.62	1.81
	1.37	0.75	1.745	1.62	0.87	2.055	1.5	1	2
Average	1.461	0.944	1.933	1.524	0.775	1.911	1.488	0.739	1.857
S.D.	0.295	0.272	0.281	0.122	0.100	0.125	0.158	0.248	0.181

Subject: RS

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity Image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	2.12	0.25	2.245	1.62	0.37	1.805	2.12	0.5	2.37
	1.87	0.37	2.055	1.75	0.5	2	2.12	0	2.12
	2	0.5	2.25	1.75	0.75	2.125	2.25	0	2.25
	2	0.62	2.31	1.75	0.37	1.935	1.5	0.25	1.625
	2.12	0.62	2.43	2	0	2	1.75	0.25	1.875
	1.87	0.75	2.245	2.37	0	2.37	1.87	0.37	2.055
	2	0.25	2.125	1.75	0.5	2	2.25	0	2.25
	2.12	0.62	2.43	2	0.75	2.375	1.87	0	1.87
	1.87	0.25	1.995	1.87	0.25	1.995	1.87	0.62	2.18
	1.87	0.25	1.995	2	0.25	2.125	1.62	0	1.62
	2	0.25	2.125	2	0.37	2.185	2	0	2
	2.12	0.25	2.245	1.87	0.62	2.18	1.87	0.87	2.305
	2	0.25	2.125	2	0.25	2.125	1.87	0.25	1.995
	2.25	0	2.25	2	0.25	2.125	2	0.37	2.185
	2	0.37	2.185	1.87	0.5	2.12	1.87	0.37	2.055
	2	0.25	2.125	2.12	0	2.12	2	0.37	2.185
	2	0.37	2.185	2.12	0.5	2.37	1.75	0.87	2.185
	2.12	0	2.12	2.25	0	2.25	1.87	0.25	1.995
Average	2.018	0.346	2.191	1.949	0.346	2.123	1.914	0.297	2.062
S.D.	0.107	0.207	0.124	0.197	0.244	0.155	0.197	0.283	0.211

Subjec AC

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	2.62	1.37	3.305	2	0.5	2.25	2.25	0.25	2.375
	2.62	1.37	3.305	1.12	1.62	1.93	2.37	0.75	2.745
	2.37	0.37	2.555	2.25	0.75	2.625	1.75	0.87	2.185
	2.62	0.75	2.995	2.12	0.62	2.43	2.37	0.87	2.805
	2.5	0.75	2.875	2.37	0.62	2.68	1.62	0.5	1.87
	2.37	0.62	2.68	2.12	0.62	2.43	2.12	0.62	2.43
	2.25	0.62	2.56	2.12	1.12	2.68	2.75	0.5	3
	2.5	0.37	2.685	2.37	0.62	2.68	1.75	0.5	2
	2.37	0.62	2.68	2.37	0.62	2.68	1.87	1.37	2.555
	3	0	3	2	0.75	2.375	1.37	0.37	1.555
	2.37	0.5	2.62	2.37	0.62	2.68	1.75	0.37	1.935
	2.5	0.5	2.75	2.25	0.75	2.625	2.25	1.25	2.875
	2.62	0.37	2.805	2	0.75	2.375	2.5	0.5	2.75
	3	0.25	3.125	2.5	0.75	2.875	2.25	0.87	2.685
	2.5	0.75	2.875	2.12	0.5	2.37	2.12	0.5	2.37
	1.87	1.37	2.555	1.25	1.12	1.81	2	0.87	2.435
	3	0.25	3.125	0.75	1	1.25	2.12	0.75	2.495
	2.25	0.87	2.685	2.5	0.37	2.685	2.37	0.75	2.745
	2	1	2.5	2	1	2.5	2	0.62	2.31
Average	2.491	0.668	2.825	2.031	0.774	2.417	2.083	0.688	2.427
S.D.	0.302	0.393	0.253	0.478	0.290	0.389	0.339	0.269	0.383

Subjec AB

	Crossed Disparity Image			Uncrossed Disparity Image			Zero Disparity image		
	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.	Sphere	Cyl.	Eff. Sph.
	2.12	0.5	2.37	1.25	0.25	1.375	0.87	1.5	1.62
	1.87	0.25	1.995	1.12	0.5	1.37	1.62	0.87	2.055
	1.62	0	1.62	1.5	0.25	1.625	1.5	0.62	1.81
	2	0.25	2.125	1.12	1.62	1.93	1.37	0.87	1.805
	1.87	0.25	1.995	1.25	0.25	1.375	1.12	0.5	1.37
	1.87	0.25	1.995	0.62	0.25	0.745	1.37	0.5	1.62
	1.5	0.25	1.625	1.62	0.37	1.805	1.5	0.37	1.685
	1.87	0.37	2.055	1.37	0	1.37	2.25	0.62	2.56
	2	0.5	2.25	1.25	0.25	1.375	1.87	0.37	2.055
	1.75	0.62	2.06	1.25	0.25	1.375	1.5	0.37	1.685
	1.5	0.25	1.625	1.25	0.5	1.5	2	0.62	2.31
	1.87	0.37	2.055	1.25	0.25	1.375	1.5	2.5	2.75
	1.75	0.37	1.935	1	0.25	1.125	1.25	0.5	1.5
	2.12	0.62	2.43	1.25	0.37	1.435	1.5	0.25	1.625
	1.37	0.75	1.745	1.37	0.5	1.62	2.87	1.25	3.495
	1.37	0.87	1.805	0.87	0.25	0.995	1.62	0.25	1.745
	1.62	0	1.62	1.25	0.37	1.435	1.25	0.87	1.685
	1.62	0	1.62	1.62	0.37	1.805	1.25	0	1.25
	1.75	0	1.75	1.12	0.25	1.245	1.62	0.37	1.805
	1.87	0	1.87	1.25	0.62	1.56	1.12	1	1.62
Average	1.766	0.324	1.927	1.229	0.386	1.422	1.548	0.710	1.903
S.D.	0.223	0.260	0.252	0.231	0.320	0.275	0.443	0.554	0.527